THE CHAOS OF KATRINA

THESIS

Gerald W. Morris Jr., Captain, USAF

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DEPARTMENT OF THE AIR FORCE
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AIR FORCE INSTITUTE OF TECHNOLOGY

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Gerald W. Morris Jr., BS

Captain, USAF

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Gerald W. Morris Jr., BS
Captain, USAF

Approved:

____________________________________ _______________
Bradley E. Anderson, Lt Col, USAF (Chairman) date

____________________________________ _______________
Alan W. Johnson, PhD (Member) date

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Abstract

This study is a case study of federal logistics support during Hurricane Katrina disaster relief operations. Data from federal contracts covering the first ten weeks of Katrina are used to measure federal logistics activity. The study investigates whether chaos theory, part of complexity science, can extract information from Katrina contracting data to help managers make better logistics decisions during disaster relief. The study uses three analytical techniques: embedding, fitting the data to a logistic equation, and plotting the limit-cycle. Embedding and fitting a logistic equation to the data were used to test for deterministic chaos. The logistic equation and two versions of the limit-cycle model developed by Priesmeyer, Baik and Cole were also tested as potential management tools.

This study found deterministic chaos was present during the first week of disaster relief, but inconclusive results for subsequent weeks possibly due to internal changes to the relief dynamics. The research concludes that the initial conditions and early actions will have a significant affect on disaster relief outcome. Furthermore, many events that appear to be uncontrollable and random may actually be controllable. Therefore, managers play a critical role in preparing for and providing guidance in the early stages of disaster relief.

To my wife and two sons

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I would like to express my sincere appreciation to my faculty advisor, Lt Col. Bradley Anderson, for his guidance and support throughout the process of researching and writing this thesis. His insight and experience was a tremendous help. I would also, like to sincerely thank my wife and our two sons for their unceasing patience, support, and understanding throughout my studies here at AFIT.

Gerald W. Morris Jr.

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I. Introduction

Background

On Thursday, August 25, 2005 a tropical storm in the Caribbean was upgraded to hurricane status, which was not unusual since it was the heart of hurricane season. By Friday of the week, the same hurricane, newly named Katrina, was predicted to become a category four hurricane and a serious threat to the Gulf Coast from Alabama through Louisiana. The same day, Friday, the governors of Louisiana and Mississippi declared a state of Emergency for their respective states. On Saturday, people in Louisiana and Mississippi began evacuations in anticipation of Katrina. On Sunday, President George W. Bush declared Louisiana a federal disaster area. The Superdome was opened as a place of refuge on the same day. On Monday, August 29, 2005 at 6:10 CDT Katrina made landfall (Committee, 2006: Ch 5). This is only the beginning of the disaster that has been called the worst natural disaster in modern American history - Hurricane Katrina (Townsend, 2006:1).

Hurricane Katrina affected a huge area. Over 90,000 square miles were devastated and much of the local infrastructure destroyed. Millions of people had their lives thrown into disarray (Carafano, 2006). Furthermore, although the total number of people who died as a result of Katrina may never be known for certain, it has been

estimated to be over 1,300 ("Death," 2006:1). The economic damage caused by Katrina was huge as well. It has been estimated at $225 billion, which would make it America's most expensive disaster (Wolk, 2005). Out of this estimate, the federal government has already allocated over $108 billion to help rebuild the effected infrastructure and provide financial aid to survivors (DHS, No Date). Especially hard hit was New Orleans. It had escaped the initial wrath of Katrina only to be inundated with water as the dikes in New Orleans' levees broke. Although Katrina devastated the Louisiana and Mississippi gulf coast, making the disaster worse to many survivors was the agonizingly slow relief caused by poor government logistics performance. The US Senate report on the disaster, "A Nation Still Unprepared," did not mince words in its critique of the relief effort. The report indicated there was a failure at all government levels to take the threat of possible catastrophe as a result of the hurricane season seriously. Although Katrina had been tracked for days prior to landfall, the government failed to take action, and failed repeatedly after landfall to provide adequate relief. The report laid blame on federal, state, and local governments for not doing more to help prepare for disaster and to quickly respond in the aftermath of Katrina. Furthermore, the report claimed, "The results were tragic loss of life and human suffering on a massive scale, and an undermining of confidence in our government's ability to plan, prepare for, and respond to national catastrophes" (Committee, 2006: 2). This has significant ramifications.

First, Katrina was not the only catastrophic hurricane that was plagued by poor local, state, and federal response; Hurricane Andrew was another ("Disaster Management," 1993). Poor federal disaster response to Andrew culminated in the Federal Emergency Management Agency (FEMA) and Department of Defense (DoD)

changing their disaster related plans and policies to prevent similar performance in future disaster relief operations (Youngbluth, 1996: 1-6). Nevertheless, lessons learned from Andrew were either not applied or were not enough to prevent a repeat of the poor performance during Hurricane Katrina. In addition, the year prior to Katrina a joint government exercise, Hurricane Pam, was conducted based on the scenario that a category three hurricane makes landfall in New Orleans. The exercise identified the possibility of the levees in New Orleans failing resulting in flooding the city. It also foresaw significant deaths, the need to evacuate between 200,000 and 300,000 people and other ominously similar details experienced during Katrina. Nevertheless, significant lessons learned from the exercise were not applied prior to Katrina (Committee, 2006: Ch 8).

Second, many Americans considered the terrorist attacks of September 11, 2001 to be a watershed event that was supposed to alert all Americans to the possibility of other attacks or threats to our way of life. Katrina serves as a reminder that the United States is not as prepared for catastrophe as many people would like to think it is. Meteorologists know prior to landfall when a hurricane is approaching and their reports allow people a few days to prepare. This is not the case with most other disasters. Hurricane Katrina should not have caught the nation as unprepared as it was (Committee, 2006: note).

Finally, statistically Americans can expect to see more frequent severe storms in the future. For years, meteorologists and other scientists have been studying the effects of global warming. Whether it is a natural phenomenon or caused by human activities, global warming is having an effect on weather patterns (Position," 2005; "Global,"

2006). For instance, a study found an 80 percent increase worldwide in Category four and five hurricanes, the most severe type. Also, in the past thirty-five years there has been an increase in the total number of hurricanes in the North Atlantic (Webster and others, 2005:1844-1846; Kerr, 2005: 1807). Hurricane Katrina was one such storm.

Disasters, especially those as catastrophic as Katrina destroy more than homes and infrastructure, they destroy lives. Many people are killed, more are physically injured either directly from the disaster or because they are unable to get help for pre-existing conditions because of the disaster. Even if spared life and limb, some will still suffer from mental anguish and many will carry their emotional scars for life.

Problem Statement

Hurricane Katrina demonstrated that the government was still not prepared to manage logistics in the aftermath of a catastrophic disaster, despite after action reports from previous disasters, clear storm warnings and several days to prepare prior to Katrina's arrival. Furthermore, after Katrina made landfall, there was still a lack of leadership, communication, and coordination, and resources were often not apportioned correctly (Committee, 2006: 2). Although there were well established plans, logistics support during Katrina still performed poorly and appeared to quickly become uncontrolled. The disaster has been the catalyst for many inquiries as to why things went wrong in the relief effort and in placing blame on various individuals and organizations. Although no one level of government or agency is likely to blame for the poor logistics response to Katrina, this research will focus on the federal government's response. This is due in large part because the federal government has the responsibility of providing support to local and state governments. In short, the federal government is the supplier of

resources that cannot be arranged by other means. Also, contracting data were selected as the means of measuring government logistics support. This is because the federal government contracted out much of its logistics support during Katrina (Cooper, 2005: Introduction). Furthermore, information regarding the contracts is readily available to the public, thanks to requirements for government oversight and openness ("Katrina Contracts," 2007). The intent of this research is to provide managers with information concerning disaster logistics dynamics, and introduce tools that can identify characteristics of this dynamic that may be useful for managers. For instance, can the data shed light into the disaster environment and identify whether a policy change at a given point in time will help control events or make them more uncontrollable? Also, can it identify whether there is a pattern in the disaster relief dynamics that was overlooked or unrecognized that may indicate how the operation is evolving and how managerial decisions affect the disaster outcome?

Research Objective

Can an area of complexity science called chaos theory be used to extract useful information from the Katrina data that will help managers make better logistics decisions during disaster relief?

Investigative Questions

IQ 1: Does data from Hurricane Katrina exhibit characteristics that can be explained by chaos theory?

IQ 2: Does this data reveal an underlying pattern that could be useful to management for decision making?

IQ 3: Does this data reveal information about the level of control exercised by the government in awarding contracts during Katrina?

IQ 4: Can the data be used to estimate the extent or limit of logistics support that would eventually be needed?

Methodology

This research is a case study of federal logistics support during Hurricane Katrina. It consists of a mixed method design, using quantitative data and analysis in the context of a qualitative study (Leedy and Ormrod, 2005: 97). It analyzes the data using pattern matching, which is comparing actual or empirical data to a theoretical model (Yin, 2003:116). In this case, it compares actual contracting data from Hurricane Katrina to chaos theory models. The unit of analysis is organizational, because it looks at contracting data from the federal government as a whole.

The first step in implementing the methodology is to collect federal contracting data from Katrina and prepare this data so that it can be compared to the theoretical models. Next, two of the most often used chaos theory models will be applied to the contracting data to evaluate if the data supports the contention that they follow what would be expected from chaos theory. That is to say, does the data contain deterministic chaos? Finally, if the analysis supports a pattern of chaos theory, the data will be analyzed to see if it provides information that could be helpful to managers, such as being able to use it for diagnostic purposes. For instance, can the data be used to provide feedback to managers allowing them to determine if decisions they have made are having a desired effect.

Assumptions and limitations

This study is a case study of Hurricane Katrina. Therefore, a major limitation to this study is that it relies on the events of one disaster. Hurricane Katrina is a disaster that stretched the nation's ability to cope with the destruction that followed. It is being looked at singularly to test previous findings based on combined data from multiple disasters, to see if they also apply to a single disaster. Another limitation is that this research looks only at logistics processes, and not other functions such as security or coordinating search and rescue missions. It also assumes Katrina disaster relief can be looked at meaningful as a whole, rather than, or in addition to, being seen as many separate, local disasters caused by the same storm.

Finally, since chaos theory is a paradigm through which to view the disaster, it does not eliminate the possibility that other factors were also present. For instance, if chaos theory characteristics are present, it does not mean that poor communication was not a factor. What it does mean is that if future researchers want to evaluate the role of communication during Katrina, they should also look at it in nonlinear, chaos terms, rather than strictly in linear terms. For instance, if there is a breakdown in communication, in linear terms that means the communication process has been broken and obvious information flow has stopped or has been hindered. Looked at nonlinearly, the breakdown in communication begins to affect other areas often unexpectedly so that it has a multiplicative effect.

Implications

The implication of successfully matching empirical data to chaos theory is that it would indicate disaster events follow non-linear, chaotic dynamics. Initial conditions will have

a significant affect on disaster relief outcomes some of which will be unexpected. It also means events that are initially thought to be random processes may actually be deterministic, albeit complex system interactions. Most importantly, it also means events that evolve from what appears to be uncontrollable conditions or random events may in fact be controllable (Glass, 1996:101). The decisions managers make before disaster strikes and immediately afterwards will have a large impact on the success of the disaster relief outcome.

II. Literature Review

There are several valid explanatory theories as to why the logistic response during Katrina was so poor, and more than one may be applicable, and thereby provide at least a partial explanation and partial solution to the inefficiencies. Unfortunately, not all explanations are equally enlightening. In this section, three alternative explanatory theories are briefly reviewed, along with a rationale for why they were not chosen as the basis of this research. The theory forming the basis of this research, chaos theory, will then be discussed with a little more depth, including how it is applicable to disaster logistics.

Communication

The first explanatory theory to be discussed is communication theory. Communication theory may help explain why logistics failed during Katrina, and specifically use Katrina as an example of what happens when the communication process goes awry. Communication failure was problematic during Katrina, particularly during the first few days after landfall. Ground and cell phones became inoperable which had a huge affect on disaster relief. But barring this obvious example, there were other instances of poor communication. For example, the United States Senate report, "A Nation Still Unprepared," identifies that there were no plans in place to provide guidance on how responders would operate in the event there was no power or the preexisting communication infrastructure was inoperable. In addition, the National Communication

System, a Department of Homeland Security (DHS) agency, was unprepared to provide communication support to first responders (Committee, 2006:10-16).

The logistics communication failures that took place during Katrina could also be looked at in light of the classic communication process. The expected benefit from this exploration is that by understanding the communication process and why it failed during Katrina, steps could be taken to mitigate future communication failures in similar disasters. The result would be improved communication and more effective logistics.

Using the communication process to explain why logistics went poorly during Katrina has merit, and poor communication has been mentioned in several reports as the cause for poor disaster relief. In the obvious case of the telephone infrastructure becoming inoperable, it is easy enough to see that generators powering communications equipment were not protected well enough against flooding. Providing more robust protection to backup power sources may be an easy fix in hindsight, if it was merely the result of assuming the city's levees would hold. Likewise, internet and satellite communication proved useful during Katrina disaster relief, therefore, a case might be made for expanding these capabilities in disaster-prone areas for better communication redundancy. Other infrastructure problems may exist, such as differing radio frequencies and nonstandard nomenclature. FEMA is addressing this issue with the establishment of the National Incident Management System, a standardized plan for disaster response ("NIMS," No Date). As can be seen, the communication infrastructure problems are either being addressed or could be addressed in several different ways.

In other cases, depending on the level of analysis, the root communication problem may be an example of interpersonal or inter-group communication barriers. For

practical applications, rather than theoretical, communication problems might therefore be explored as an aspect of a behavioral science, such as psychology or sociology. A holistic perspective of behavioral science will be looked at in a later paragraph, as management or organizational behavior. In either case, it does not appear that exploring communication as the root cause for the logistic failure during Katrina would provide information that could directly help managers improve their logistics decision making.

Information Sharing/Supply Chain

Another explanation for why logistics was poor during Katrina is that there were significant problems within the supply chain, and that by improving the supply chain, disaster relief could be improved. Supply chain management is a relatively recent business strategy that has expanded the traditional role of logistics in commercial businesses. A supply chain is defined as the life cycle processes supporting physical, informational, financial, and knowledge flows for moving products and services from suppliers to end users (Ayers, 2004). The Council of Supply Chain Management Professionals defines supply chain in the following way:

> Supply Chain Management encompasses the planning and management of all activities involved in sourcing and procurement, conversion, and all Logistics Management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediates, third-party service providers, and customers. In essence, Supply Chain Management integrates supply and demand management within and across companies (Vitasek, 2006).

Proper attention to supply chain management has led to business efficiencies and has emerged as a means of distinguishing leading companies from their competitors. A common example of a company using supply chain management to become an industry leader is Wal-Mart. In his report to congress on lessons learned from Katrina, Dr.

Leonard from the Harvard Business School praised Wal-Mart, Lowes, and other supply chain giants for the efficient disaster relief they provided in the aftermath of Katrina. He says in the report, “Many modern firms are built around excellence in the management of their supply chains, giving them a high degree of precision in knowledge about what they have and where it is, together with the capacity to move it efficiently to where it needs to be delivered” (Leonard, 2006). Supply chain management is a strategy that has been shown necessary for logistic success even in disaster relief.

Besides the faulty logic of comparing the supply chains of Wal-Mart, a for-profit enterprise, with a continuing business interest, with the governmental disaster task force set up specifically to provide disaster aid, exploring Katrina as an example of poor supply chain management is still problematic. Supply chain management relies on information sharing. Companies have control over internal supply chain information and share this information with supply chain partners for their mutual benefit. Unfortunately, based on government reports, FEMA did not have adequate control of its supply chain information during Katrina. For instance, it was unable to maintain visibility of assets after initial deployment or requisition. This results in two major difficulties for researchers. The first is the obvious need to remedy the lack of asset visibility. This has been identified as an area of improvement for FEMA, which is already working to resolve the problem (DHS, 2005). The second problem is the lack of empirical data necessary for modeling and comparing solutions. Consequentially, while looking at Katrina from a supply chain perspective also has merit, it would be difficult to study with the available data.

Management/Organizational Behavior

A third explanatory theory for exploring why logistics failed during Katrina is Organizational Behavior. Organizational Behavior is a combination of several behavioral sciences used to derive multidisciplinary and often practical insight helpful to managers. It can be used to help explain why an organization, or individuals within an organization behave in the matter they do, and more importantly, what changes should be made to the organization so that desired behavior is more likely (Gibson and all, 2006:6-9). This line of exploration could lead to many insightful findings about what may have contributed to logistics failure during Hurricane Katrina.

For example, one type of organizational culture is termed Bureaucratic Culture. A bureaucratic culture is one that relies on formal control and is focused on internal processes, organizations that typify this culture include military and government agencies (Gibson and all, 2006:37-38). This culture may have had an effect on government disaster relief during Katrina. For instance, DHS including FEMA as well as DoD appeared hampered by several layers of authority. Both FEMA and DHS were frustrated by the amount of time it took for DoD to take action on requests for assistance. Even the White House found the process overly formal and slow, and described the process as the "21-step" approval process (Committee, 2006: Ch 26, 19). It was also frustrating from the military perspective; many units were already preparing to assist with the disaster relief prior to and immediately after landfall of Katrina and were surprised at the lack of requests for assistance received in the first few days (Committee, 2006: Ch 26, 25).

Other areas of Organizational Behavior could be explored such as the role individuals, especially leaders, played in logistics during Katrina. It could also explore the extent that intergroup behavior and conflict played in Katrina relief logistics.

Organizational Behavior explanations for the failed logistics during Katrina relief hold promise for many areas of research at all levels of analysis. However the majority of the research inquiries in this area require an intimate knowledge of either individuals or organizations involved in Katrina relief operations.

Chaos Theory

The final explanatory model and the one selected for this study is chaos theory. Chaos theory is part of a larger body of knowledge known as Complexity Science. At its heart is the idea that what initially looks like random events may actually be part of a very complex pattern that is practically unpredictable, but that has as its source nonrandom events. This section will provide a brief background into chaos theory, provide some characteristics of deterministic chaos systems, and discuss general applications. It will then briefly describe some specific applications pertinent to this research. Specifically, it will review the application of chaos theory to management, supply chain management and disaster management.

Background.

Chaos theory was first hinted at by Henri Poincaré in 1903 in his essay, “Science and Method.” The King of Sweden had sponsored a contest to provide proof that the solar system, as modeled by Newtonian physics, was dynamically stable. Unfortunately, Poincaré was unable to find a complete solution, but as a result of his tremendous work

was awarded the prize anyway. In his essay, he noted, “small differences in the initial conditions produce very great ones in the final phenomena” (“Henri,” No Date).

This phenomenon was also experienced by Edward Lorenz, a meteorologist at MIT. He was working on a computer weather simulation and decided that instead of restarting a long sequence, he would save time by reentering data from an earlier run of the sequence at a midway point. However, after about an hour into the new run, Lorenz noticed that the computer had created an entirely new and completely different weather pattern from what he had expected. After some investigation, it turned out the data created the new weather pattern because of rounding. The computer held six decimal places, but the data reentered only went to three decimal places. The 0.000127 that was left off the reentered data was enough to create an entirely different weather pattern in the computer simulation. Lorenz wrote a paper on this phenomenon, which popularized the effect and thereafter it has been known as the “Butterfly Effect” (“What is Chaos,” No date).

As a result of Lorenz and Poincaré, scientists and researchers became interested in this and related phenomenon and their research gave rise to chaos theory. Chaos theory defines chaos as data that is non-linear and too complex to use for predicting data points, but has limits and is deterministic. Further research also gave rise to related phenomena such as Complex Adaptive Systems. These phenomena are generally grouped together as Complexity Theory/Science (Singh and Singh, 2002:23).

Characteristics.

According to chaos theory, deterministic chaos systems can be classified into two primary behaviors, stable and chaotic. The area between them is often referred to as the

"edge of chaos" (Rosenhead, 1998). A stable system is one in which the behavior tends toward a particular outcome, even when disturbed, it will return to this initial outcome. That is to say, its outcome is the same as if it would have been had it not been disturbed. A chaotic system however is one which is sensitive to even small disturbances. A small disturbance to a chaotic system will result in a different outcome than it would have been had it not been disturbed. As one would expect, systems at the edge of chaos are flexible, that is to say, they are easier to change than a stable system, but are not as sensitive as chaotic systems. In applying chaos theory to management, it is systems at the edge of chaos that are interesting to most researchers.

Systems of deterministic chaos display the following characteristics: Sensitive to initial conditions, time irreversibility, attractors, fractional forms/geometry and bifurcation. The first characteristic, being sensitive to initial conditions, is the one discovered by Poincaré and Lorenz. It is summed up well by the description of how Lorenz came upon the phenomenon. This characteristic is also what makes chaos theory non-linear. The next characteristic is time irreversibility. Systems displaying chaos are so complex, that the initial conditions often can never be repeated, only nearly so. This is especially true when looking at natural systems. Attractors are another characteristic. Attractors are the conditions that the system gravitates towards. In a stable system there is one attractor. "Edge of chaos" systems have two to eight attractors and in chaotic systems many attractors. Some are called strange attractors if they lead to an unexpected result. Attractors can be a single point or a collection of points, such as an orbit ("What is Chaos," No date). Figure 1, below, illustrates a two-attractor system. The system can

be seen to oscillate over time, settling quickly to two *y*-values. They are approximately 5.6 and 7.7.

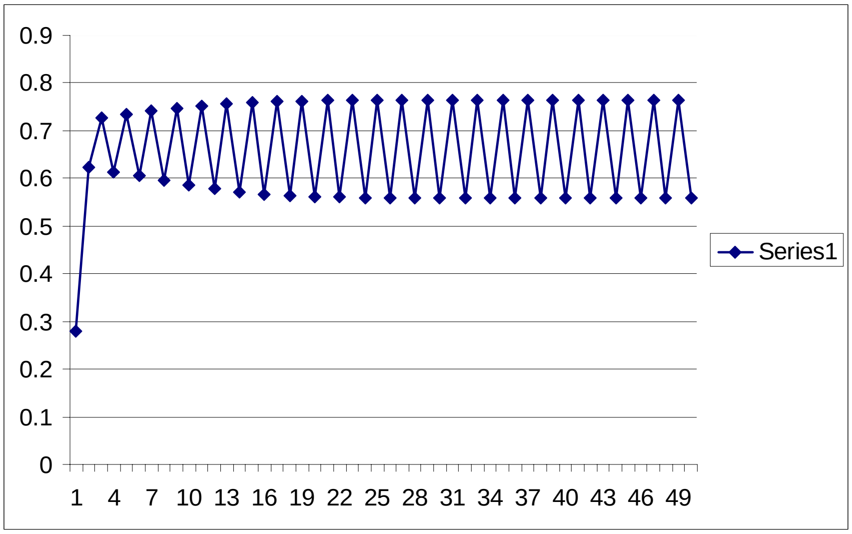


Figure 1. Illustration of two-attractor system

Fractional forms also called fractional geometry are a visual characteristic of some deterministic chaos systems. It is a phenomenon in which any section of a curve or surface appears the same when compared to a magnification of the same image. The Koch Curve is an example of fractional geometry (Clayton, 1997). This is illustrated below in figure 2. It can be seen that level two in the figure is merely a reproduction of the same triangle pattern as the generator level at one-third scale and evenly spaced on the surfaces. This replication rule, continues through level three and higher levels.

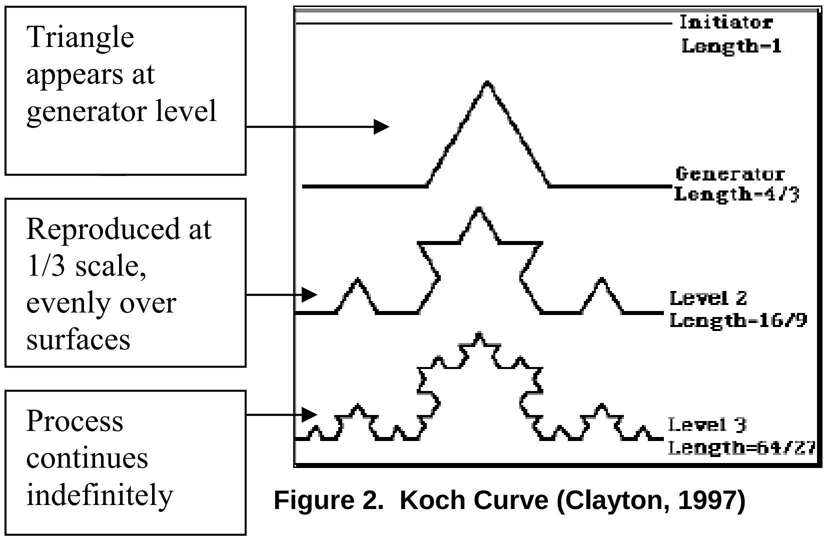


Figure 2. Koch Curve (Clayton, 1997)

Another characteristic of deterministic chaos systems and the last to be discussed is bifurcations. Bifurcations are points where the system becomes so disturbed that the current number of attractors cannot continue to contain the solutions or behavior, so that it causes the number of solutions or attractors to double. For instance, if a stable one-solution system becomes disturbed too much it will mutate into a two-solution system. If the disturbance continues it might bifurcate into a four-solution system. The logistic map below, in figure 3, illustrates the possible solutions to a system. With low parameter values, expressed as r in the diagram, one solution is possible. As the value of r increases to approximately r = 3, the number of possible solutions bifurcates into two solutions. This process continues to bifurcate until after r = 3.57, when the system cascades into an indefinitely large number of bifurcations.

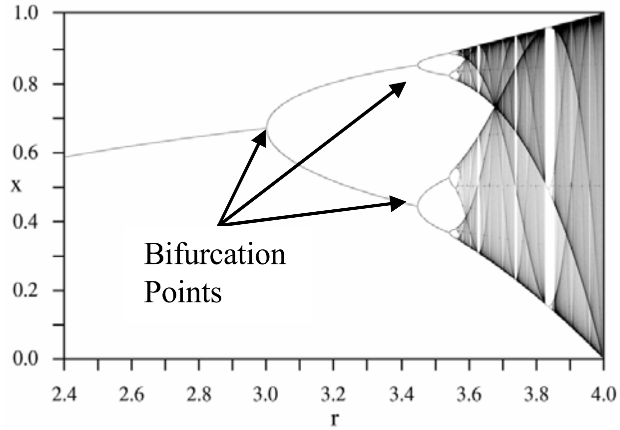


Figure 3. Bifurcation points on Logistic map ("Bifurcation," 2006)

Applications.

Chaos theory was first used by mathematicians and physicists to help them understand turbulence such as found in weather patterns and smoke fumes ("What is Chaos," No Date). It later spread to other sciences as varied as biology, ecology, medical research, psychology, economics, finance, and others ("Chaos and Complexity," 2006). This research is analyzing the use of chaos theory to help managers in logistics provide more efficient disaster relief. Therefore, applications important to this research are management and specifically supply chain management and disaster management.

As mentioned above, chaos theory in its early application tended to be technical and used mathematical models as the basis of research. However, some researchers have since applied the theory to situations in which data could not be quantitatively captured. In the literature this is often referred to as a metaphorical use of chaos theory (Clayton,1997). Although using chaos theory metaphorically can be helpful in

developing models or creating new paradigms to help understand complex situations, it tends to be more subjective than quantitative applications.

Chaos theory when applied to management and decision making usually takes one of two forms. The first is to provide insight into management strategies that are more effective than traditional means, given deterministic chaos is in the system. The other is how managers can use information from businesses to control companies in edge of chaos environments. Most management applications of chaos theory are as metaphorical models. In a metaphorical model, the researcher will analyze a managerial environment or condition and described it in terms of characteristics of chaos theory, even though the condition cannot be measured. For instance, if the condition can be described as being sensitive to change and having the potential for unpredictable results, the researcher would infer that deterministic chaos is present. Furthermore, if deterministic chaos is present, it infers that what is true for chaos theory systems may be true of the managerial condition.

The first study suggests that chaos theory is an appropriate model to analyze management, because the reality of organizations and their environments have changed while assumptions about them have not. For instance, three assumptions typically made about companies are that they are closed systems, the environment is stable, and there are clear management actions that have clear and predictable results. The reality, according to Glass is different. In his study, he suggests that all organizations are complex and affected by their environment, the organizations' environment is rapidly changing, and cause and effect relationships are not always clear (Glass, 1996).

An example provided in his study is that given a traditional, linear view of business, an increase in advertising expenditures results in increased sales (within the laws of diminishing returns). However, in reality an increase in advertising might push a competitor to develop a more effective advertising campaign that results in the original company experiencing lower sales than the original condition. Glass refers to this phenomenon as a vicious cycle, which he explains is a system spiraling toward negative, often unexpected outcomes. A virtuous cycle on the other hand is when the phenomenon results in the system spiraling toward positive outcomes (Glass, 1996).

As a result of his research, Glass finds that managers should acknowledge the inherently nonlinear condition of management and organizational dynamics and make adjustments to their management style. For instance, managers should move away from trying to stabilize their present condition, such as maintaining a certain percentage of market share, and instead focus their attention on the rapid shifts in their environment which might become amplified, that is become opportunities they can seize. Another management change is more flexibility in direction. For example, rather than initiating a detailed top-down strategy, managers should provide clear organizational goals. Management should also cultivate a learning environment with empowered employees to improve its likelihood of seizing opportunities as they arise (Glass, 1996). Glass's conclusions are similar to that of other researchers into chaos theory applications in management (Young and Kiel, 1994; Singh and Singh, 2002:23).

Another study shows that chaos theory goes against the traditional view of management, which is to provide formal control in a stable environment. Instead, as with Glass, Young and Kiel suggest that decentralized control and a quick, responsive

workforce is in more harmony with chaos theory ideals. Young and Kiel summarizes the role of the manager this way, “The task of the postmodern manager is to expedite bifurcations which produce desirable attractors and, at the same time, to control key parameters to stabilize such outcome states for a firm while framing organizational policy in such a way as to not destabilize the larger political economy” (Young and Kiel, 1994).

Another study provides a critique of applying complexity theory to management. It discusses whether complexity science should be applied to management and if so, its limitations. In his study, Rosenhead finds that management topics, unlike hard sciences, cannot be proven. Management concepts are either empirically supported or not. Furthermore, much of the quantitative research is based on computer simulations which are then analyzed to see how well they mimic empirical observations, rather than being based on the empirical observations themselves. So Rosenhead claims that while research applying complexity science to management assumes universal applicability of the results, they are open to debate on how representative they really are. Rosenhead also makes a distinction between the metaphorical use of complexity science, and its use as an analogy. For instance, he gives the example of using an automobile as a metaphor for the economy by using terms such as, “applying the brakes” or “a touch on the accelerator,” to describe actions affecting the economy. He doubts anyone using a metaphor in this way would use it as the basis to change to the system. It just makes the underlying concept being analyzed clearer (Rosenhead, 1998). As an analogy however, complexity science might be more useful than a metaphor. Many important scientific breakthroughs have been the result of using a known phenomenon as a predictive model to analyze a new one. Unfortunately, Rosenhead concludes that complexity science does not meet key

criteria that are needed to use it as an analogy for management. Among the needed criteria is that complexity science should be more understood than management theory and that there should be precise similarities between the two phenomena. Rosenhead does however provide hope that this inapplicability is not a permanent condition. He writes, "This situation could well change, as complexity theory develops further, or as management complexity writers refine their analysis. However, at present the conceptual basis seems inadequate to support testable analogical insights" (Rosenhead, 1998).

Chaos theory has also been specifically applied to supply chain management. For the most part, this research has been in two areas. First, it has been applied to the amplification of errors within a supply chain, a phenomenon that has been termed the "bullwhip effect." It has also been applied to the phenomenon in complexity science in which systems develop order out of disorder. This is referred to as self-organization (Wilding, 2006; Choi and others, 2001: 351). The case of error amplification is more applicable to this study. It is an example of a system that is sensitive to initial conditions, not unlike the findings of Poincaré and Lorenz.

In the first example, Wilding addresses a problem that could arise as a result of managers attempting to keep their supply inventories levels too low. In his study, Wilding used an automated smoothing technique to control inventory levels; a common means companies use to control their supply levels. The algorithm resulted in using old forecast data for making new forecasts, which caused errors to be amplified. The result was chaos or instability being introduced into the system. Wilding writes, "a system that is meant to control fluctuations, and consequently buffer the system from instability, can create dynamics that turn a stable demand pattern into one that is unpredictable with

occasional explosive changes in demand" (Wilding, 2006: 5). Wilding reports in his research that it is corroborated by the inventory management study of John Sterman from MIT. Sterman found that when policies to lower inventories are introduced, costs could increase by as much as 500 percent higher than optimum as a result of stock outages and erratic ordering (Wilding, 2006).

The phenomenon of error amplification has also been studied by other researchers. For instance, Laugesen and Mosekilde analyzed this phenomenon in the BEER Game. The BEER game is a management game developed at the Sloan School of Management. The game is played by individuals or teams who assume the role of a particular link in the supply chain, such as producer, wholesaler, or distributor. The retail player orders "beer" from the wholesaler, based on customer demand. The wholesaler then orders beer from the distributor, and this process continues up through the supply chain to the producer. Each link has a built in delay, which causes demand amplification or the bullwhip effect that characterizes the game. In their study, computer simulations of the BEER game were made and the results examined. Laugesen and Mosekilde found interesting forms of bifurcations, and other elements characteristic of deterministic chaos systems in their simulations. In the conclusion of their study, Laugesen and Mosekilde report similarities between their simulations and actual economic dynamics. They believe the oscillations in the systems they studied, significantly contribute to the formation of business cycles (Laugesen and Mosekilde, 2006).

Chaos theory has also been applied to disasters and crisis. These studies have looked at chaos both metaphorically and quantitatively. For instance, in the first study chaos theory is applied metaphorically to public relations during disasters. One of the

points Murphy makes in her study is that an organization may be able to influence disaster events up to a point, after which it becomes uncontrollable. She writes, “chaos theory stress that these cataclysmic moments are not random, but rather the culmination of accumulated ‘noise’ within the system itself. Put another way, certain organizations contain flaws within themselves that amplify over time to self-generate crisis independent of outside factors” (Murphy, 1996: 106). Murphy suggests that it may be possible to control change, by influencing the system prior to the point when the system enters chaos. That is to say, to influence the system while it is still at the edge of chaos. Using the example of the Exxon Valdez oil spill off the coast of Alaska, Murphy explains that Exxon was criticized for not taking control of the oil spill, quickly and missing the opportunity for creating a positive public opinion. This is contrasted to the actions of Johnson & Johnson. After the Tylenol tampering scare, Johnson & Johnson’s quick action led to a positive public outcome rather than the negative one as with Exxon. Murphy also points out the affects of strange attractors. Using rumors as an example, she points out, “Organizations often try to combat rumors with facts. However, if rumors are indeed chaotic systems, facts will have little permanent effect against the underlying cultural anxieties that govern response to a given product, company, or technology” (Murphy, 1996: 107). In other words, the rumor is a reflection of the dominant cultural attitude. It is the attractor or point of stability and can only be changed when there is a bifurcation of the cultural attitude.

Another study used a quantitative approach to apply chaos theory to disaster management. This research was presented at a conference in May 1995, entitled, “What Disaster Response Management Can Learn from Chaos Theory.” Two researchers,

Priesmeyer and Cole, presented a paper in which they use a logistic regression model to analyze a data set of 257 respondents in 106 different disaster events. The equation used in the model is the logistic equation which is also known as the predator-prey equation. The equation contains one variable, referred to as X in Priesmeyer and Cole's study and one parameter, k. The logistic equation is then fitted to the empirical data at various k- and X-values to find the best values to fit the data. Comparing the empirical data to the theoretical model resulted in an F-value of 6.75, which was significant at the 95 percent confidence level. Their research resulted in a k-value of 3.66 during the first 24-hours, which is near 3.7; the number they report as the threshold of chaos in their model. They interpret the value of k to indicate the level of stability in the environment. Priesmeyer and Cole concluded that their results provide quantitative evidence that disaster response is nonlinear and has characteristic of deterministic chaos. They report the k value of 3.66 is an ideal level, because it indicates that disaster response was flexible but not chaotic. Their conclusion is, "chaos which results during these first 24 hours is a necessary and desirable condition which accommodates adaptation, cross-communication, the suspension of rules or policies, and other emergent behavior essential to an efficient response" (Priesmeyer and Cole, 1996).

In the same paper, Priesmeyer and Cole provide a management tool to evaluate the evolution of disaster response by analyzing the change of two closely related resources over time. Their study used the need for Emergency Medical System (EMS) personnel and equipment and firefighting personnel/equipment as the two related resources. The change in resources is plotted on a Cartesian plane, and analyzed as to whether there is an increase or decrease in the change in demand of each resource. The

quadrant in which the change is plotted determines the direction of growth of the disaster response (Priesmeyer and Cole, 1996).

The same May 1995 conference also provided information on how social time impacts chaos theory and self-organization. Social time is the concept that the responders' perception of time, and not just the time that has actually elapsed, has significance. The conclusion of the attendees at the conference is that managers could learn several things from chaos theory. For instance, they learn that disaster response should be flexible and adaptive. Other lessons are that managers should look for fluctuations which might indicate bifurcation points, managers should be catalysts of change deliberately causing bifurcations, and disaster infrastructure should be flexible enough to allow response to self-organize (Koehler, 1996).

Limitations.

Although chaos theory provides insight into disaster relief, it has limitations as well. First, as with any model, it is an approximation of reality and not the reality itself. There are likely other models that could provide insight into a different aspect of disaster relief. It is unlikely that any one model will be able to explain every aspect of reality. A second limitation is not every organization that provides disaster relief is affected by the disaster in the same way. Some organizations may be heavily stressed, while others play periphery roles (Koehler, 1996). Finally, disasters are naturally complex. Consequently, other problems may exist. For instance, if inter-organizational conflict is present, it may or may not represent a condition that leads to instability, but chaos theory does not address the root cause of the conflict.

The quantitative examples provided by Priesmeyer and Cole presented at the May 1995 conference were based on data from several disasters combined together rather than looking at them one at a time, unlike the present study. Comparing chaos theory models to federal contracting data during Katrina should provide insight into the logistics failures during Katrina. The comparison should be able to discriminate between whether the failure was due to random events, or instead by poor management decisions. If the later is the case, then it may be possible to control events through changes made by knowledgeable managers.

There are other valid theories to explain why the logistic response during Katrina was so poor. Furthermore, these theories may provide at least a partial explanation and solution to logistics inefficiencies. However, not all explanations are equally enlightening. This section provided background into three alternative explanatory theories with a rationale for why they were not chosen as the basis for this research. It also provided a description of chaos theory, the model chosen for this study.

III. Methodology

Overview

The objective of this study is to answer the research question: Can an area of complexity science called chaos theory be used to extract useful information from the Katrina contracting data that will help managers make better logistics decisions during disaster relief? The methodology chosen for this research is a case study. Yin mentions that a case study is an appropriate research methodology for explanatory studies, when researchers want to answer questions relating to "how" or "why" and do not require control of behavioral events. Furthermore, he provides an example of when this approach is appropriate, "Thus if you wanted to know how a community successfully overcame the negative impact . . . you would be less likely to rely on a survey or an examination of archival records and might be better off doing a history or case study" (Yin, 2003:6). This study analyzes whether chaos theory is useful in "explaining" the poor logistics support during Hurricane Katrina and might also provide useful insights for managers making logistics decisions. Just as Priesmeyer and Cole's research found the presence of deterministic chaos in general disaster relief, this study should provide insight into whether there is evidence of deterministic chaos in a specific catastrophic disaster, Hurricane Katrina. If deterministic chaos is present, it would indicate that initial conditions of disaster response would have a significant affect on the relief's outcome, and furthermore some of the events which are thought to be random or evolve from uncontrollable earlier events may actually be controllable. If this is the case, then the success or failure of logistics support during disaster relief operations relies in large part

on the decisions logistics managers make prior to, and during the initial onset of the disaster.

This study relies on a mixed method design. A mixed method design combines quantitative and qualitative components in research (Leedy and Ormrod, 2005: 97). In this study, quantitative data was obtained on the federal contracts awarded in support of Hurricane Katrina. This data will be analyzed using pattern matching, which is comparing actual or empirical data to a theoretical model (Yin, 2003:116). The theoretical model in this case is chaos theory. The case study design and questions, however, are qualitative in nature. The quantitative results of the research will be used to answer qualitative questions, and therefore, the mixed method design of this study.

Federal contracts related to Katrina were chosen as the source data for two reasons. First, it appears an appropriate means of quantifying federal logistics activity. Federal agencies rely on contracting to bridge the gap between what is needed from the agency and what they are able to provide with internal resources. This is especially true in the case for logistics commodities and services. According to David Cooper, Director, Acquisition and Sourcing Manger in the Government Accountability Office (GAO), federal agencies are increasing the trend of contracting out work. Federal agencies responding to Katrina provides a case in point. Cooper reports, “The government’s response to Katrina and Rita, for example, depended heavily on contractors to deliver ice, water, and food supplies as well as the effort to patch rooftops and supply temporary housing to displaced residents and evacuees” (Cooper, 2005: Introduction). The second reason is that the data is readily available. The contracting data from Katrina are available from the Federal Procurement Data System-New Generation (FPDS-NG).

These data are also publicly assessable, which increases the ability for other researchers to replicate or verify the study ("Katrina Contracts," 2007). Since, the contracting data is federal government-wide, the unit of analysis for this study is organizational.

Data

Although the contracting data from the FPDS-NG is publicly assessable, it comes with a disclaimer, "Many contracting offices supporting Katrina, particularly those relocated to the disaster recovery area, do not have access to their normal contract writing systems and thus have not been able to populate FPDS-NG contemporaneously with the contract awards they have made. Others have not had time to enter data due to the tempo of operations. It is impossible to estimate the impact this may have on the total numbers" ("Katrina Contracts," 2007). The data used in this study was current as of 4 January 2007 and is assumed to have the majority of the contracts awarded during Katrina, albeit this is a limitation of the data. The full database contains 13,907 contracts awarded by 22 departments, some representing several federal agencies. Out of this database, only contracts effective between 28 August and 5 November 2005 are used. The narrowed database covers the first ten weeks of relief effort, beginning 28 August. This date was chosen, because it was the last day that had zero contracts awarded prior to the main Katrina relief effort. All the dates in the study contained data with values greater than zero. The narrowed database used in this study contains 5,544 contracts.

The contracting data used in the study are both the number of contracts which became effective on a given day and the total dollar value of the contracts that became effective on that day. These values became the measures of interest in this study. A preliminary study was also conducted using the contracting pay categories, or value

bands. The use of value bands as a means of analyzing the data will be discussed further in Chapter 4, Results and Analysis.

After the data were collected, they needed to be prepared for analysis. Scale was a concern when using the number-of-contracts and contract-values data in the same equation. It also became a concern when using the logistic equation which requires data values between zero and one. So, a means to normalize the data needed to be found. The typical method of normalizing data used in the logistic equation, when it is used to estimate populations, is to calculate it as the percent of the maximum possible population for each point in the time series. So for instance, if the maximum population for a particular environment is one million, and the value at a given point in time is 500,000, then the data would be measured as 0.50 or 50%. Since the maximum number of contracts and the maximum available funds for contracts on a given day is not known, another means of normalizing the empirical data needed to be found.

The solution chosen was to measure each day's value as a percent. The total activity for all seven weeks and weekly totals were both used as denominators in calculating percents. The percentage was calculated differently depending on the system being modeled. For instance, in the case of analyzing a ten-week system all 70 days of the data points were used to determine the daily value. Each day was a percent of the total amount for all 70 days, this can written as:

$$P_i = x_i/\sum_{i=1}^{70} x_i \qquad (1)$$

Were P_i is the percent at a given (i) day, and x is the value at a given (i) day.

For the one-week system models, the percent was calculated using weekly totals to calculate daily values. This method can be described as:

$$P_i = x_i / \sum_{i=1}^{7} x_i \qquad (2)$$

As with the previous formula, P_i is the percent at a given (i) day, and x is the value at a given (i) day.

The data generated by the logistic equation was similarly normalized by calculating it as a percent using the same method as with the empirical data. So for instance, if the empirical data is measured as the percent of the total for the week, the data generated by the logistic equation was likewise measured as a percent of the total for the week. This allows a comparison of the chaos model with the empirical data using the same scale.

There is a rationale for measuring the disaster relief time series both as ten-week systems and as one-week systems. As dynamic as logistic support is during disaster relief, the system is likely being adjusted and continually changed. To illustrate, consider contracting agents. They award contracts based on particular needs and then will evaluate whether the contracting activity was able to meet those needs. Further contracting activity will then attempt to either readdress needs not initially met, or meet new needs. Each time this redirection takes place, it changes the system. The significance of this is that the system may be continually changing and it may not be possible to describe the whole ten-week system with one parameter. Because of this, the data for the first ten weeks will be looked at both as ten-week systems and as one-week systems.

The reason one-week systems were chosen is because there is a compromise in trying to capture the dynamics of a continuously changing system and having enough data points to make a comparison. Considering it is common to look at our personal and professional lives in terms of days, weeks, and months; taking a slice of the time series at weekly intervals seems a natural choice. Looking at the data by week might be exemplified by managers who use weekly staff meetings for feedback to make adjustments in their decisions and policies. In this study, the week runs from Sunday to Saturday.

Investigative Questions

To meet the objective of this research and guide the study, investigative questions were developed. These questions are:

IQ 1: Does federal contracting data from Hurricane Katrina exhibit characteristics that can be explained by chaos theory?

IQ 2: Does this data reveal an underlying pattern that could be useful to management for decision making?

IQ 3: Does this data reveal information about the level of control exercised by the federal government in awarding contracts during Katrina?

IQ 4: Can the data be used to estimate the extent or limit of logistics support that would eventually be needed during disaster relief?

Answering investigative questions

The investigative questions will not be present in numerical order. Investigative question three provides detail on the characteristics and dynamics of the logistic equation, which is used to generate the data for the theoretical model in the embedding process.

The embedding process is used to answer investigative question one. Therefore, investigative question three will be addressed first, which will allow the basics of the logistic equation to be explained and allow readers a better understanding of the principles being used in later applications of the equation.

Investigative Question 3.

Does this data reveal information about the level of control exercised by federal agencies in awarding contracts during Katrina?

The logistic equation was chosen to analyze the amount of control in the system, because it is one of many models that can be used for this purpose. In addition, Priesmeyer and Cole used it specifically with disaster response to verify that the data reflected, what they would consider, an appropriate level of stability/control during the first twenty-four hours of disaster relief (Priesmeyer and Cole, 1996). The logistic equation was initially used to describe population growth, but has since been applied to other phenomenon such as in economics and organizational science (Zimm, 2005). The logistic equation contains a parameter that quantifies the amount of stability in the environment, in this study it will be identified by the symbol lambda, "λ." At lower parameters the logistic equation data exhibits stability, as the parameter increases so does the sensitivity of the system to change. If deterministic chaos is present in a natural or empirical system, it is expected that when it is compared to the logistic equation, the parameter-λ would reflect a value that equates to the amount of stability in the system. The logistic equation cascades into chaos, at parameter values above 3.57, and would indicate a lack of control in the system being analyzed. Systems under 3.57 indicate

stable or edge of chaos conditions which is indicative of controlled systems (Priesmeyer and Cole, 1996; Harrison, 2006; Clayton, 1997).

The logistic equation is expressed as:

$$X_{n+1} = \lambda X_n(1-X_n) \tag{3}$$

In the equation X_{n+1} represents the value of the next point in the time series, X_n is the value of the current point in the time series, $1-X_n$ is a suppression element and λ is the control parameter. As originally used to describe the population growth, the population of the next generation is represented by X_{n+1}, the current population is represented X_n, and $1-X_n$ takes into account the effects of overfeeding, overcrowding, deaths, and so forth. The population growth is represented by the λ-parameter. The range of values for X in the logistic equation is between 0 and 1, and is a measure of the percent of the maximum population the environment can support. The range of values for λ is between 0 and 4. The reason the equation is closely associated with chaos theory is the interesting variation in results mentioned above that occur with different λ-parameter values. With a parameter value less than one, the population will stabilize at zero. That is to say, the population is not sustainable and dies out. At parameter values between 1 and 3 the population will stabilize to one attractor. Values larger than 3 begin to bifurcate first oscillating between two points, then four, then eight, until at a parameter value of 3.57 after which the number of bifurcations begins to oscillate between so many attractor points that it becomes chaotic (Priesmeyer and Cole, 1996; Harrison, 2006; Clayton, 1997).

In their application of the logistic equation, Priesmeyer and Cole used the amount of responder activity during a particular time frame, probably one hour, as X. (The actual

measure of time was unclear in the literature.) The time series was plotted for the first twenty-four hours and fitted to a logistic equation to determine the best X-variable and λ-parameter. Their study found a statistically significant similarity between the empirical disaster response data and the logistic equation. The parameter was interpreted as the amount of amount of stability within the disaster environment. Priesmeyer and Cole's model provides a basis of what to expect in disaster relief in general. If, however, the model is used for short slices of a time series, it allows managers to understand how stable the system is initially and how their decisions might affect the disaster response. More importantly, managers can make adjustments at the end of each time series slice using the logistic equation as a feedback source on the measure of stability and affect activity during subsequent time periods. For instance, if managers realize the environment is near chaos, they could avoid initiating policies which might increase the instability. If Katrina data is found to exhibit λ-parameter values under 3.57, it would indicate a stable system or one near the edge of chaos and therefore managers were in control of the system. Values over 3.57 would indicate a loss of control. This would indicate an inability for managers to initially cope with the disaster.

Investigative Question 1.

Does federal contracting data from Hurricane Katrina exhibit characteristics that can be explained by chaos theory?

Embedding is an appropriate means of analyzing data from Katrina to see if it contains evidence of deterministic chaos (James, 1996:44). Embedding was selected because it is a simple process, yet effective in revealing deterministic chaos. It uses a single time series to represent more than one dimension in the plot of a dynamic system.

The process consists of taking two consecutive points in a time series, to create a vector, then plotting them on a Cartesian plane. The number of points in the time series used to determine one data point on the plot defines the number of dimensions that will be plotted. For instance, given a time series of a, b, c, d, and e; three dimensions could be plotted by assigning x-, y-, and *z*-coordinates as illustrated below in table 1 (James, 1996:44: Clayton, 1997; Shockley, 2005: 150):

Table 1. Assigning values to *x, y*, and *z* for 3-diminsional embedding

Plot data point	***x-coordinate***	***y-coordinate***	***z-coordinate***
1	*a*	*b*	*c*
2	*b*	*c*	*d*
3	*c*	*d*	*e*

Examples of time series known to exhibit deterministic chaos and known to be random are provided below to illustrate the differences in the dynamics of two types of systems. The logistic equation was used to generate data that characterizes deterministic chaos.

In the first plot, data was generated by the logistic equation using $X = 0.5$ and $\lambda = 2.9$ and is illustrated below in figure 4. The λ-parameter = 2.9 describes a system with a one-point attractor, it can be seen in figure 4 that the data oscillates before it quickly

settles down to its stability point, or attractor. This movement is similar to a pendulum coming to rest after being disturbed.

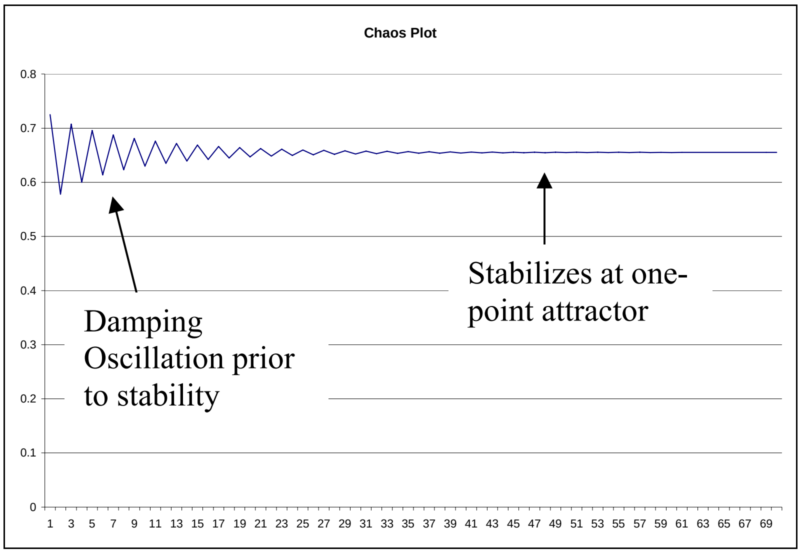


Figure 4. Time series of logistic equation, *X = 0.5, λ = 2.9*

The same data plotted in figure 4, is embedded in three dimensions in the plot illustrated in figure 5. Note that the line created by the data becomes denser toward the center. This is where the system stabilizes to its attractor.

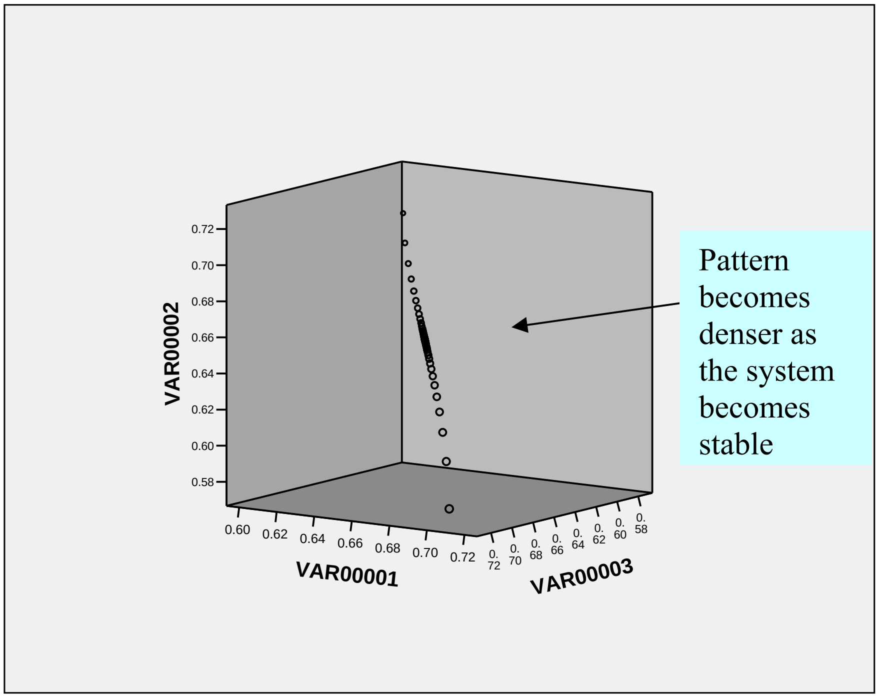


Figure 5. Three-dimensional plot of embedded time series, *X = 0.5, λ = 2.9*

A time series for a logistic equation using $X = 0.5$ and $\lambda = 3.7$ is illustrated below in figure 6. The λ-parameter is at the level where the system has become chaotic. The plot of the system in figure 6 shows some pattern initially but quickly dissipates over time and is lost.

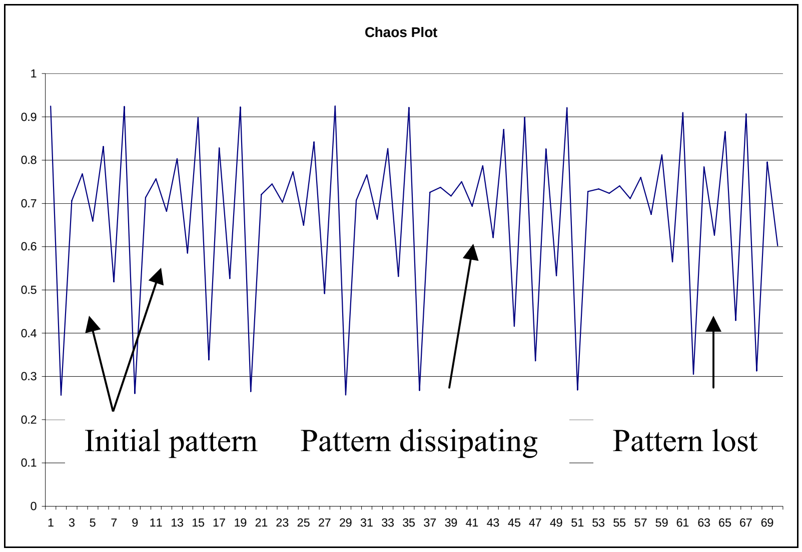


Figure 6. Time series of logistic equation, *X = 0.5, λ = 3.7*

When the same data used in figure 6 is embedded in three dimensions and plotted a pattern is seen. It appears to be an "S" shape, or curve. This can be seen in figure 7, below.

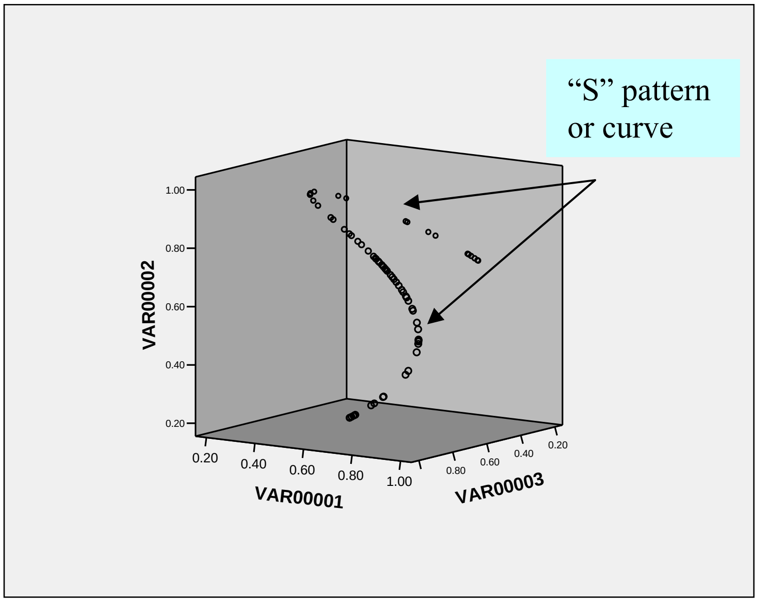


Figure 7. Three-dimensional plot of embedded time series, *X = 0.5, λ = 3.7*

Even a time series with a λ-parameter level near the upper limit of possible outcomes, $X = 0.5$ and $\lambda = 3.99$, shows a pattern when embedded. A plot of the time series appears in figure 8. There is less of a pattern apparent in this plot, than of the one in figure 6, but a careful look reveals some oscillation in the beginning before it becomes chaotic.

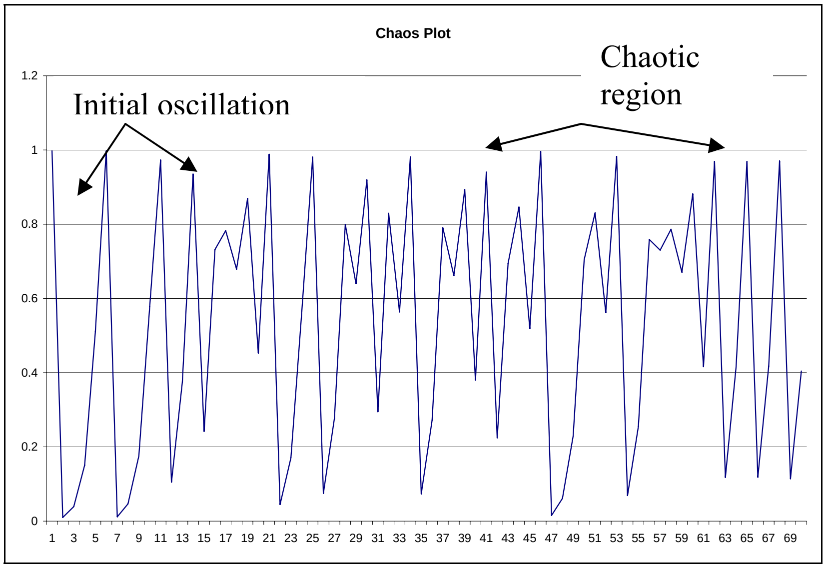


Figure 8. Time series of logistic equation, *X = 0.5, λ = 3.99*

The embedded time series of the same data used to create the plot in figure 8 is illustrated in figure 9. The three-dimensional pattern in the embedded plot appears to form a continuation of the shape in figure 7. It looks as if the curve loops back around forming a boomerang shape.

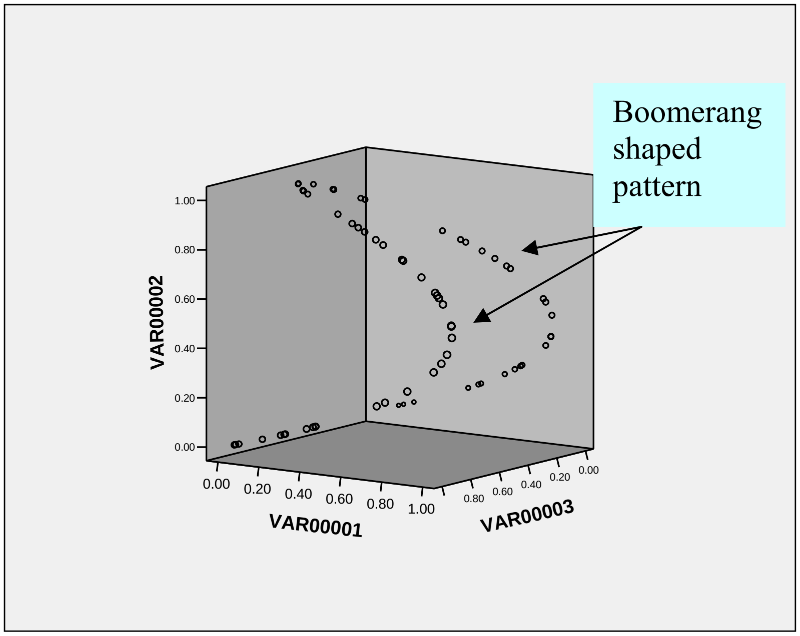


Figure 9. Three-dimensional plot of embedded time series, *X = 0.5, λ = 3.99*

As can be seen in all of the embedded plots of data generated by the logistic equation, a process which is known to generate data with deterministic chaos, a distinctive pattern emerges. In the cases illustrated, they can appear as a line, an "S" shape, or boomerang shape. In contrast, figure 10 illustrates an embedded time series of random data, taken from a normal distribution. The data appears as a cloud clustered toward the center of the plot with no other pattern.

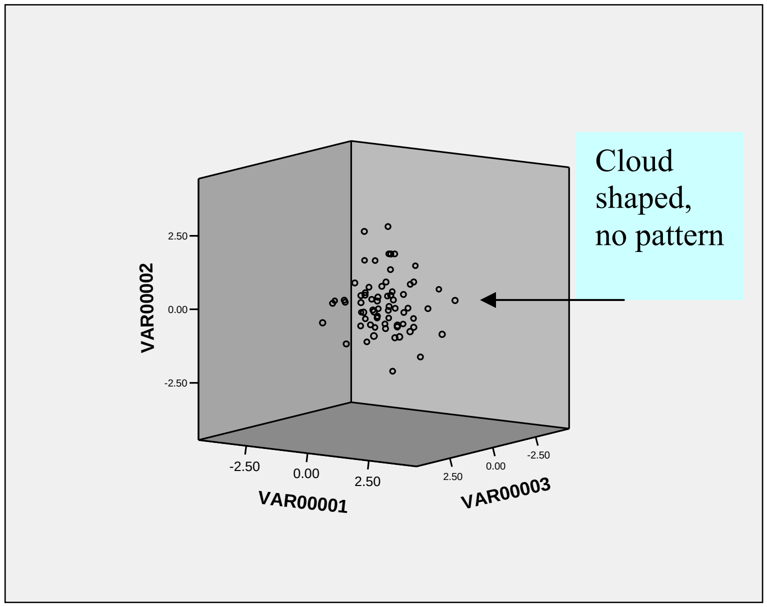


Figure 10. Three-dimensional plot of embedded random, normal dist. time series

In this study, the empirical data from Katrina contracts will be embedded in three dimensions, and then will be visually inspected. If the data is composed primarily of deterministic chaos, the data should create a distinctive pattern similar to the results illustrated above in figures 5, 7 and 9. If however, the empirical data resembles the embedded plot illustrated above in figure 10, it would not support the conclusion that there was deterministic chaos in the Katrina data.

Investigative Question 2.

Does this data reveal an underlying pattern that could be useful to management for decision making?

If an analysis of data is found to contain deterministic chaos, the usefulness of this information is limited to knowing that the events were not random, but deterministic and possibly controllable. This information may be helpful in creating a new paradigm, but

not in everyday management decisions. If a system exhibits deterministic chaos, the next question becomes how to control the events. How can managers determine when a system might undergo a bifurcation, or system change, and what should they do to affect the outcome? Logistics managers need information that they can use to make better logistics decisions.

Two types of limit-cycle models and a velocity plot were chosen as a means of providing feedback to managers on the disaster relief dynamics. These were chosen because one of the limit-cycle models was specifically identified by Priesmeyer and Cole as a means of management feedback for disaster response. They used the model on the combined disaster data, but the question remains, if it can be used by managers for a specific disaster. This is the use apparently intended by Priesmeyer and Cole (Priesmeyer and Cole, 1996). This model will be referred to as the disaster limit-cycle model. The other limit-cycle model and velocity plot are similar to the first model. They were used by Priesmeyer and Baik in another study using the limit-cycle model in a business application. The other limit-cycle model will be referred to as the business limit-cycle model. Since the business model limit-cycle was developed first, it will be discussed first. Both types of limit-cycle models and the velocity plot, require two related variables. In their business model, Priesmeyer and Baik used quarterly profits and sales as the related variables. In the disaster model, Priesmeyer and Cole used fire equipment/personnel and Emergency Medical System (EMS) equipment/personnel as the related variables.

In addition to these models, fitting the logistic equation to empirical data can provide feedback to the manager on the amount stability present in the environment, and

therefore the amount of control that may be possible. The logistic equation model will however, be discussed later.

Priesmeyer and Baik claim that the business model limit-cycle and velocity plots can be used by managers to predict organizational performance to improve corporate decision making (Priesmeyer and Baik, 1989:47). This is done in a multi-step process to first determine the points to plot for a limit-cycle, then to determine the points to create the velocity plot. The first step in their business cycle model is to calculate the marginal or change in values for each variable:

$$d_{ij} = x_{ij} - x_{i\text{-}1,j} \tag{4}$$

Where d is the difference between consecutive points, x is the value of the variable at a particular point in the time series, identified by subscript i. The point just previous is subscript i-1, and subscript j identifies the variable, for instance sales or profit. Next the mean value of the differences is calculated:

$$\mu_j = \sum_{i=1}^{n} d_{ij}/n\text{-}1 \tag{5}$$

Where μ_j is the mean of the differences, $\sum d_{ij}$ is the sum of for all i for a particular variable j, and n represent the total number of observations of i (that is the number of points along the time series). The next step is to subtract the mean difference from each individual point differences resulting in the difference from the mean D_{ij}:

$$D_{ij} = d_{ij} - \mu_j \tag{6}$$

The next step is to plot the data for the limit-cycle. The first point plotted is $x = \mu_j$ and $y = \mu_{j+1}$ (x is the mean difference of the first variable, profit for example, and y is the mean difference of the second variable, for example sales). Then, the difference from the

mean (D_{ij}) for the first *j,* is paired with the difference from the mean (D_{ij+1}) for the second *j* to create consecutive *x* and *y* variables for each point. These points are then plotted to create the limit-cycle plot.

The velocity plot is constructed by taking the two difference from the means (D_{ij} and D_{ij+1}) and multiplying them together to create the *y*-variable. The *x*-variable is the time component, such as the first quarter, second quarter, third quarter, and so on. The *x*- and *y*-variables are then plotted (Priesmeyer and Baik, 1989:16).

The results of the plots are then visually observed. Some companies in Priesmeyer and Baik's study exhibited a one-period attractor, which on the limit-cycle plot appears ideally as data concentrated near the origin at a single-point. These businesses had zero velocity (horizontal line). Others businesses exhibited a two-period cycle, which was characterized by a diagonal line oscillating between points in the first and third Cartesian plane quadrants on the limit-cycle plot. The ideal velocity plot for two-point limit-cycle businesses oscillated between two regular points (zero and another value). The last group of regular business cycles was businesses with four-period limit-cycles. The ideal plot of four-period limit-cycle is a shape similar to the symbol for infinity or an eight on its side. The ideal velocity is a line oscillating between four regular points (Priesmeyer and Baik, 1989:17-19).

Likewise, Priesmeyer and Cole developed a simpler process for plotting a limit-cycle by using changes in two variables. For instance, the change in fire equipment/personnel would be the *x*-variable and change in EMS equipment/personnel would be the *y*-variable. The *x*, *y* pair would then be plotted on a Cartesian plane to reveal information about the development of disaster relief. If the plotted data moves

into the first quadrant (positive x and y), then managers would see that the need for both resources were growing. They could monitor the situation closely to see if it comes close to maximizing available resources, in which case they would need to request assistance. So, rather than looking for patterns as in the business limit-cycle model, the plotted data in the disaster model are used to diagnosis whether more or less resources are being utilized, possibly indicating a change in the disaster response development. As with the above example, it may also provide an early warning of when the activities are likely to go beyond the limit of available resources, necessitating a request for assistance (Priesmeyer and Cole, 1996).

Investigative Question 4.

Can the data be used to estimate the extent or limit of logistics support that would eventually be needed?

In a system characterized by deterministic chaos, information to discover the limits can come from the models already identified; therefore, additional models were not explored. Analysis of the results from the business and disaster model limit-cycles and fitting the logistic equation can provide information that could be used to determine the limit of support that would be needed. For instance, in the business and disaster model limit-cycle if the data reflects a regular limit-cycle, such as a period-one or period-two limit-cycle, then the limits of logistics support is established by the attractor/s. That is to say, the limit is identified by the point or the points between which the data oscillates. Likewise, the logistic equation can be used to map system performance and predict its limit. If the logistic equation is accurately fit to the data (significant F-value), and is able

to explain much of the variation (reasonable R^2-value) then the λ-parameter can be used to identify the system limit.

Methodology conclusion

In conclusion, this research is a case study of federal logistics support during Hurricane Katrina. It is concerned with analyzing data from federal contracts awarded in support of Katrina to discover if they might contain information useful for logistics managers and help them in decision-making in future catastrophic disaster relief. The research design is a mixed methodology. The data preparation prior to being used to compare the chaos theory models to the empirical data was discussed. Several chaos theory models used in this research were examined, specifically the logistic equation, embedding, and business and disaster limit-cycle models and velocity plot. It also discussed why these chaos theory models were selected.

IV. Results and Analysis

The objective of this study is investigate whether an area of complexity science called chaos theory can be used to extract useful information from the Katrina contracting data which can help managers make better logistics decisions during disaster relief. This chapter will apply the methodology discussed in the previous chapter to the empirical data from the federal contracting database. First, the raw data will be examined to see if any patterns or other distinct characteristics are present, then the data will be transformed for analysis and compared to the theoretical models. The first chaos model to be examined is the logistic equation, followed by the embedding process, then the limit-cycle models and velocity plot. There are two limit cycle models used, the business model and the disaster model. The results from each of the models will be summarize to answer the investigative questions. Finally, a conclusion of the results and analysis is provided.

Raw Data

The first step was to plot the raw contract data, and examine them for patterns or other features. The plot of raw data for contract-values (in dollars) is given in figure 11. As can be seen there is a particularly large spike in data on 2 September 2005. On this day, approximately $750 million worth of contracts became effective. This is accounted for by one contract valued at $250 million and by the aggregation of 869 less costly contracts. Looking at the timeline of events during Katrina, this corresponds to the day after Michael Brown, the head of FEMA, said he found out about evacuees in the Convention Center and that he had not heard of reports of rioting and violence ("Big

disconnect," 2005). It was also the same day congress approved an initial Katrina relief package for $10.5 billion ("Congress," 2005).

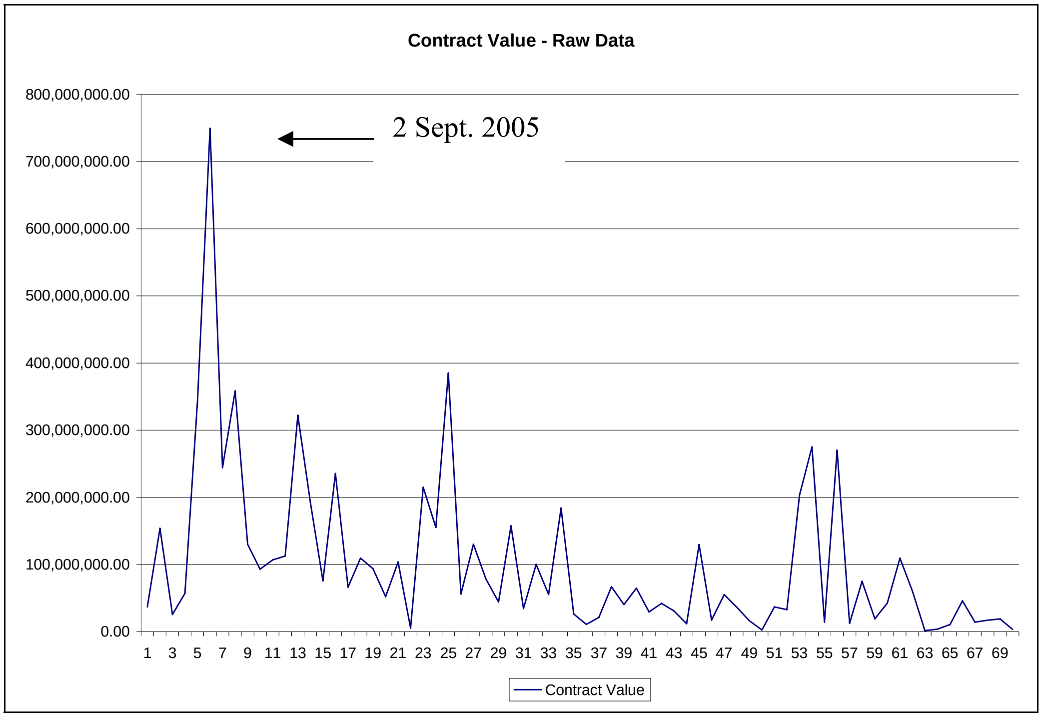


Figure 11. Plot of raw data for contract values (in dollars)

The plot of the raw number-of-contracts data becoming effective on a given day is shown in figure 12. As can be seen in this plot, there is a spike in contract numbers on 2 September and 30 September 2005. On 2 September 870 contracts became effective; of this number, 742 were awarded by FEMA and categorized as Firefighters/Community relations ("Katrina Contracts," 2007). The events related to this date are discussed above. The other spike occurred 30 September 2005, which coincides with the end of the federal

government's 2005 fiscal year. This date did not have any significant Katrina events associated with it, so the anomaly is probably related to the end of the fiscal year activities. There is also a noticeable pattern in the number-of-contracts data. This is created by a decrease every Sunday in the number of contracts becoming effective.

There is also a relationship between the number-of-contracts data and the value, as one might suspect; however it was not a one-to-one correlation. An analysis of the data correlation between contract numbers and contract-values data is 0.72, based on the raw data.

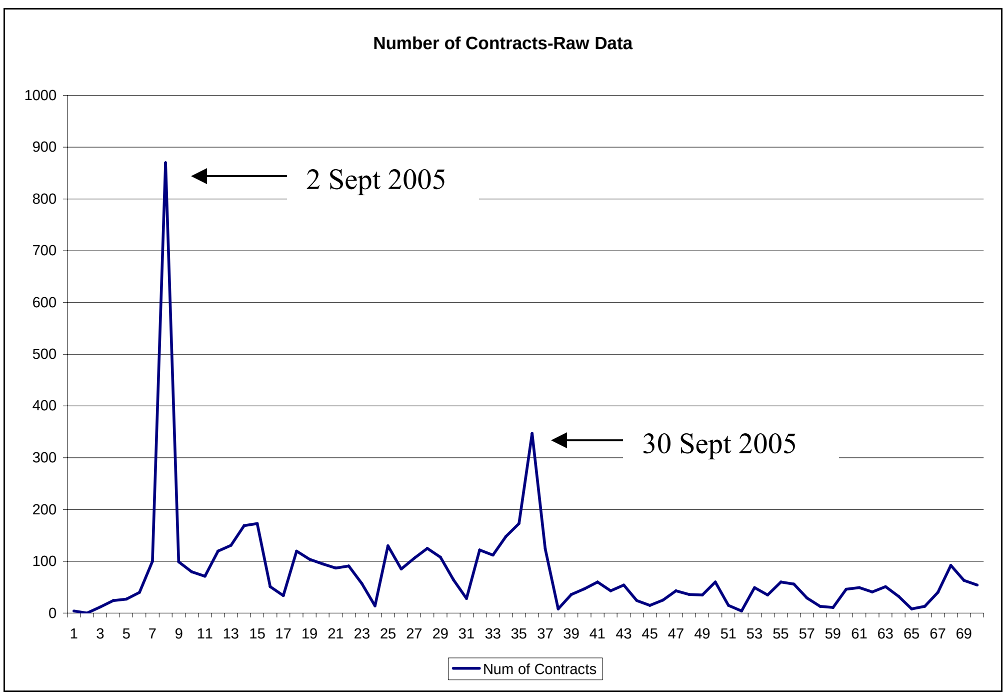


Figure 12. Plot of raw number-of-contracts data

Value Bands

The value bands used in the preliminary study were based on the categories established by the Federal Acquisition Regulation (FAR). For instance, micropurchases are contracts valued at up to $2,500 and do not require competition. This limit can be raised to $15,000 during contingencies. The next category is simplified acquisitions, which is capped at $100,000 normally and $250,000 during contingencies, and finally commercial items which is normally capped at $5 million (Poole and Welch, 2005: 2). The result of plotting the raw data of the number of contracts in each value band was similar to the results obtained by plotting the number-of-contracts data. Analyzing the bands in whole and by week resulted in findings similar to those based on the number-of-contracts data. In particular, the category of contracts under $15, which accounted for one-third of all the contracts, was remarkably similar. Due to this similarity of results when using the contracts segregated into contract value bands and the aggregation of the contracts, using value bands as a means of analysis was not pursued.

Testing for Chaos

Logistic Equation.

This study uses the logistic equation, in a manner similar to that of Priesmeyer and Cole in their study. In this study X represents one day of logistics activity, measured as a percent of either the value of contracts or the number of contracts. As with the earlier study, the λ-parameter is the unknown to be calculated. The contracting data in this study was used to look at both the first ten weeks of Katrina activity as 10-week systems, and as one-week systems.

The fit of a logistic regression line was first applied to the contract-values data based on the 10-week system. This was analyzed by SBSS statistical software and the result is below in figure 13. The curve appears as a typical, albeit nonlinear, regression line.

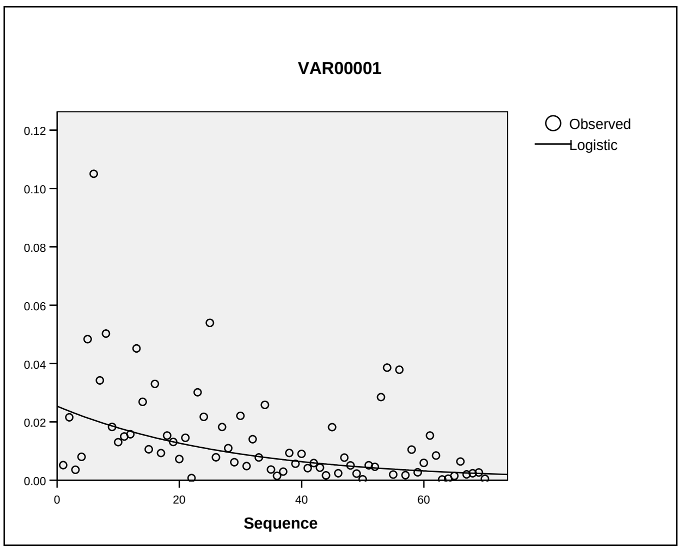


Figure 13. Logistic curve fit to 10-week system for contract-values data

The parameter SBSS estimated for the contract-values data was $\lambda = 1.035$, which if taken as a measure of environmental stability suggests the system is stable. The F-value for the fit is 29.7, which is significant at alpha less than 0.001; however, the R^2-value is 0.304, which means that approximately 70% of the variation cannot be explained by the regression line. A similar analysis was made for the number-of-contracts data using the 10-week system. This fit is illustrated below in figure 14. It should be noted, the fit appears closer than does the data in figure 13. This is due to the presence of outliers and

a phenomenon known as the “King Kong” effect. The King Kong effect takes its name from a theoretical study on the relationship of weight to height in a sample of gorillas in which one extreme value, King Kong, is added. The addition of King Kong to the sample of gorillas skews the height and weight data and effects their correlation. This makes it appear that there is a greater relationship between weight and height of gorillas than there was prior to adding King Kong (Makridakis, Wheelwright, and Hyndman, 1998: 197-198).

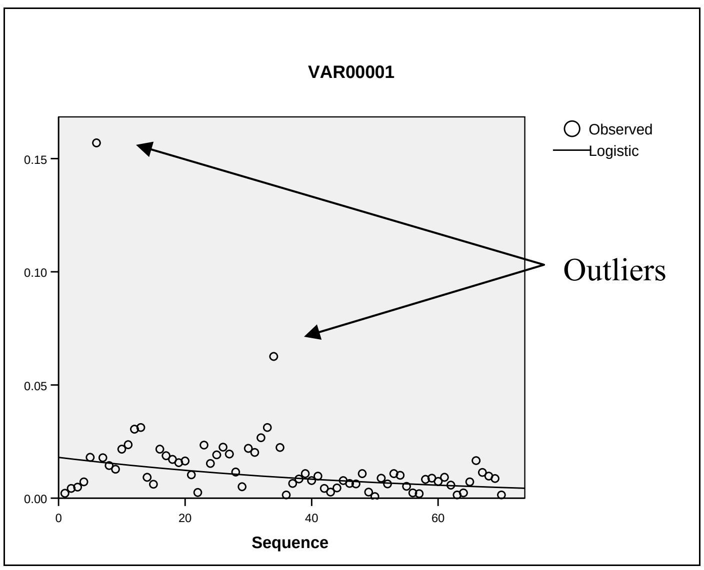


Figure 14. Logistic curve fit to 10-week system for number-of-contracts data

SBSS estimated a parameter value for the number-of-contracts data of $\lambda = 1.019$, which if interpreted as a measure of environmental stability also indicates a stable system. The F-value for the fit is 13.9, which is significant at alpha less than 0.001; the R^2-value, however, is 0.17 and indicates that the logistic regression line cannot explain 83% of the

variation in the model. In both logistic regressions, there was a good fit to the data, but the R^2-values suggest there might be a better model to explain the variation. Also in both cases, results indicate the systems are stable; nevertheless, it uses one parameter to describe the stability of the entire ten weeks of relief operations.

As mentioned earlier, the problem with analyzing a ten-week system is that it does not take into consideration changes in the system dynamics. Each time managers make changes to it, the parameter will also likely change. So, another analysis was made based on one-week systems. Each week was analyzed using Excel Solver to find the parameters to best fit the empirical data using the logistic equation. The empirical data was first put into an Excel spreadsheet along with the logistic equation. A nonlinear algorithm was used in Excel Solver to identify the best X and λ that when applied to the logistic equation would most closely match the empirical data. This was accomplished by assigning X- and λ-values as changeable cells in Solver. The Sum Squared Error (SSE) was used as the object to be minimized. Although a nonlinear algorithm was used, several systematic runs needed to be made to ensure the result was not just a local optimum. Below, table 2 provides the result of the fit test of the logistic equation to the contract-values data. The r-value in the table is the correlation between the fitted logistic equation and the empirical data for the week. The closer the correlation is to one, the closer the fit is between the two models. Note that weeks one, six, and eight of the contract-values data have high correlations and the associated parameter-λ is over 3.57, or in other words, they are in the chaotic region.

Table 2. Logistic equation fit results for contract-values data

Week	1	2	3	4	5	6	7	8	9	10
X	0.0008	0.500	0.865	0.081	0.202	0.028	0.336	0.003	0.111	0.007
λ	3.66	1.22	3.84	4	3.88	3.72	4	4	4	3.92
SSE	0.012	0.036	0.021	0.028	0.016	0.004	0.070	0.010	0.045	0.025
r	0.97	0.37	0.72	0.84	0.88	0.95	0.64	0.96	0.71	0.86

The same method was used to analyze the number-of-contracts data. The results are illustrated below in table 3. The r-values in table 3 are not as high as in the previous example table 2, and indicates the fit is not as close as with the contracts-value data. Weeks one, four and six have the highest correlations and also have parameter-λ values above 3.57.

Table 3. Logistic equation fit results for number-of-contract data

Week	1	2	3	4	5	6	7	8	9	10
X	0.0005	0.141	0.068	0.068	0.928	0.022	0.93	0.93	0.069	0.908
λ	4	1.8	4	4	3.93	3.58	4	4	4	2.68
SSE	0.053	0.016	0.003	0.006	0.026	0.006	0.008	0.022	0.014	0.035
r	0.95	0.50	0.89	0.90	0.71	0.91	0.85	0.74	0.77	0.55

It is interesting to note that in both tables, most weeks resulted in a fit that is in the chaotic region, the region with a λ-parameter 3.57 or greater. It is also interesting to note that both tables indicate that week two was in the one-attractor stability range. They had λ-parameter values between 1 and 3, but they both also had the least close fit. Week ten was inconsistent in its measurement of stability when comparing contract-values and number-of-contracts data for the same week.

As a visual illustration of how close the fit is based on the correlation results, two examples were embedded in two-dimensions and plotted so that the logistic data generated can be visually compared to the empirical data. In the figures, plots based on contract-values data are on top, plots based on number-of-contracts data are on the bottom. They also have the data generated by the logistic equation on the left and the empirical data on the right. The two-dimensional embedded plot for week one is displayed below in figure 15. In this particular example, the correlation was relatively high. There was a slightly closer fit between the contract-values data with its logistic model, than with the number-of-contracts data with its logistic model. The correlation between the contract-values data with its logistic model is 0.97, and the number-of contracts has a 0.95 correlation. The similarity between the theoretical models and the empirical data can clearly be seen in the figure. Another important characteristic of this plot is the horseshoe pattern created by the data. This is characteristic of a system with a purely deterministic chaos dynamic in the chaotic region with a λ-parameter value of 3.57 or higher.

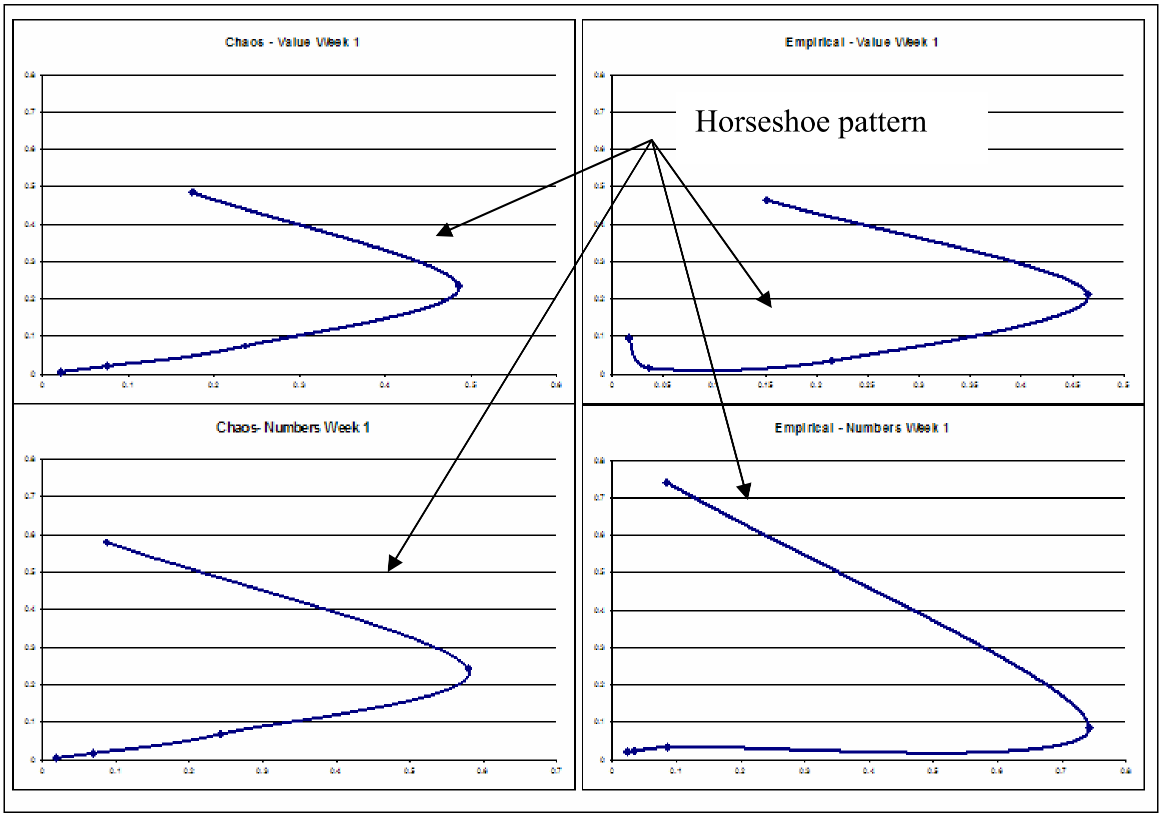


Figure 15. Plot of logistic generated data and empirical data for week one

However, not every week resulted in a close fit between the logistic equation and the empirical data. The plots for week two illustrate a lower correlation between the empirical and theoretical models. This lower correlation results in the inconsistency found in the plots for week two exhibited below in figure 16. Visually the empirical data does not resemble the chaos model for either the contract-values or numbers-of-contracts data sets.

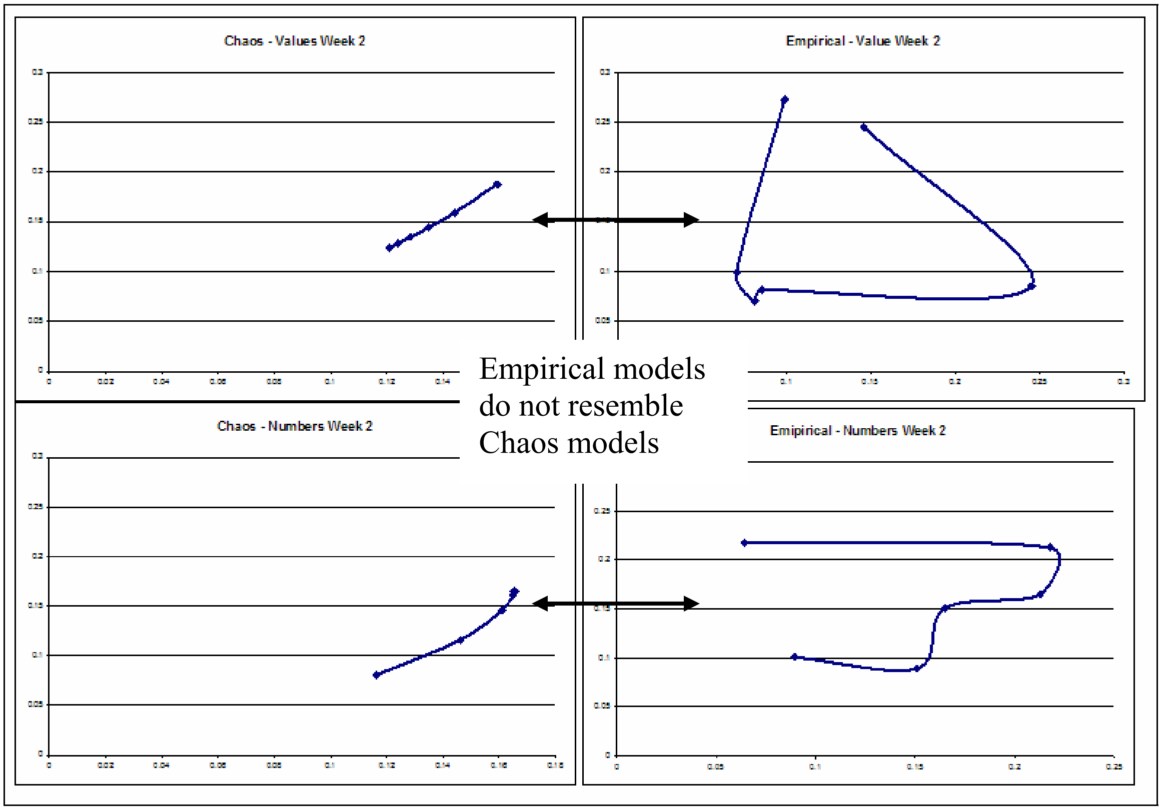


Figure 16. Plot of logistic generated data and empirical data for week two

The other weeks also did not have a consistent fit with empirical data. Some weeks had a better fit than others. The average fit for the contract-values data is a correlation of 0.79 and the average fit for numbers-of-contracts data is a 0.78 correlation. Plots of weeks three through ten are exhibited in Appendix A.

Investigative Question answered by Logistic Equation.

Investigative question three asked, does this data reveal information about the level of control exercised by federal agencies in awarding contracts during Katrina? According to the results of the ten-week system, it was in control and stable. However with a relatively low R^2-value, using only one parameter to measure the first ten weeks does not appear appropriate. The model could not explain most of the variation.

According to the one-week systems, most weeks were in or near the region of chaos. The shorter timelines appeared to fit the logistic equation model to the empirical data better. The high parameter values would indicate that the systems were not controlled. An interesting result is that the two-dimensional embedded plots for week one, which had the best fit, also resembled a purely deterministic chaos system in the chaotic region.

Embedding.

A three-dimensional model of the contracting data from Hurricane Katrina was created using the embedding process. The time series was plotted using SBSS statistical software, because it has the capability to graph in three dimensions. The result of using the contract-values data based on a ten-week system is displayed below in figure 17. It does not appear to form any distinctive patterns as would be expected if deterministic chaos was present. Rather, it more closely resembles random data, as plotted in figure 10.

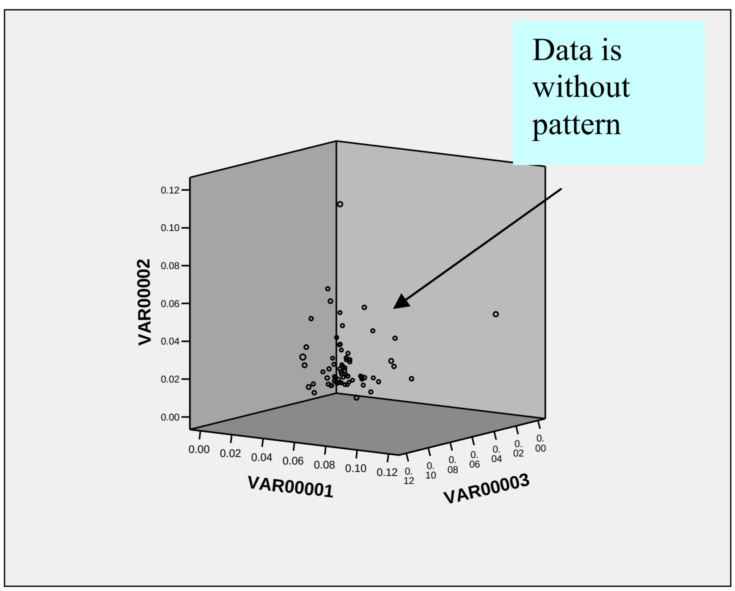


Figure 17. Three-dimensional plot of embedded time series of contract-values data

Likewise, the result of using the number-of-contracts data is displayed in figure 9. What appears to be a pattern toward the middle of the plot is a concentration of the data due to outliers (it is actually one outlier projected into three dimensions). If the outliers are removed the plot also resembles random data, and is without pattern. Note that the reason the scale appears small in figures 17 and 18 is that the data points being measured are as a percent of all values for ten weeks. Therefore, each day is a small portion of the total for the 70 days. The outliner is the spike of activity on 2 September 2005.

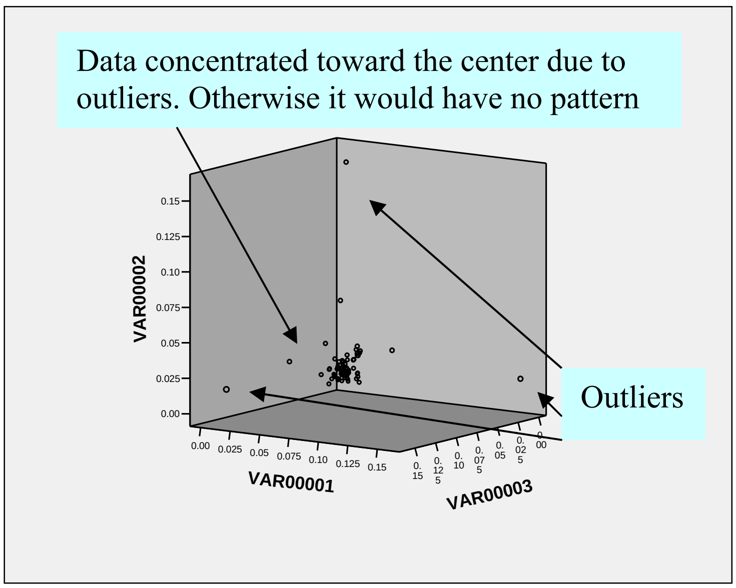


Figure 18. Three-dimensional plot of embedded time series of number-of-contracts

Similar plots were made based on the one-week systems. The problem in embedding one week of data is that with each dimension added in the embedding process, a data point is lost. For instance, with seven days in a data set, a two

dimensional plot results in six data points, and a three dimensional plot results in only five data points. It becomes difficult to ascertain if there is a pattern or not with fewer data points. Combining the one-week systems together does not make it one system; therefore, putting them together does not result in a system recognizable as containing deterministic chaos. For instance, figure 19 below illustrates the plotted data generated by the logistic equation that best fit each week of empirical data combined into one three-dimensional plot. It is not recognizably different from a plot of randomly generated data.

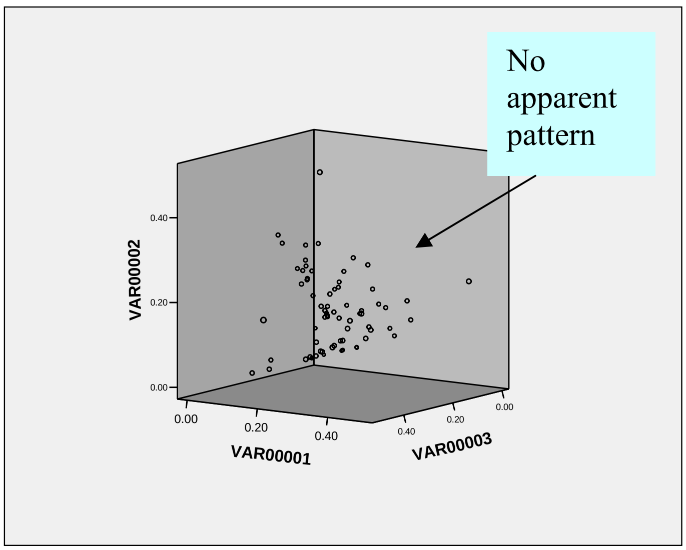


Figure 19. Logistic equation generated data (used to fit contract-values data)

The same is true for the values generated by the logistic equation used to fit the numbers-of-contract data, exhibited below in figure 20. What appears as a pattern in the center disappears when the outliers are removed. Taking the outliers out also brings the plot into the same scale as in figure 19. Note the limit of the plot in figure 19 is at 0.40 and the limit in figure 20 is 0.80. Since the logistic equation generated data is known to

exhibit deterministic chaos yet appears as random data in figures 18 and 19, the empirical data would not be expected to be distinguishable from the random data either. Individually, plots of the weeks in two dimensions would resemble the comparisons made of weeks one and two in figures 15 and 16 above.

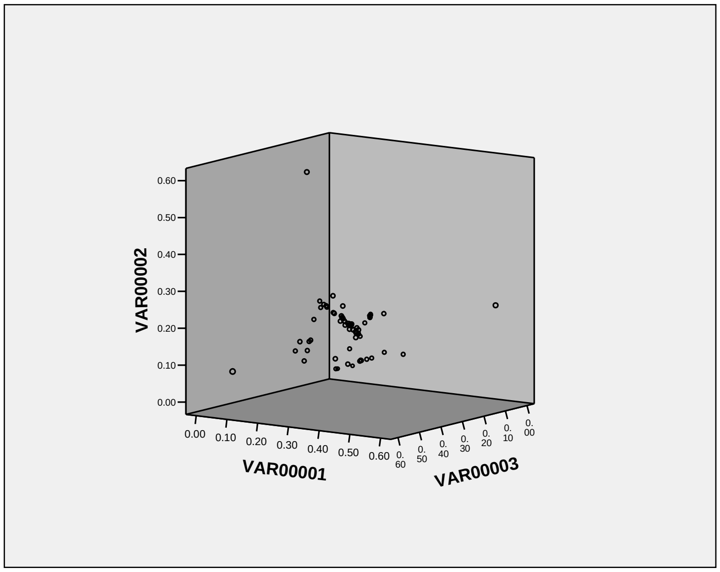


Figure 20. Logistic equation generated data (used to fit number-of-contracts)

Investigative Question answered by Embedding.

Investigative question one is, does federal contracting data from Hurricane Katrina exhibit characteristics that can be explained by chaos theory? After analyzing the various plots of the ten-week systems and one-week systems, the empirical data from Katrina does not appear to form a pattern as would be expected if deterministic chaos was present. They appear to more closely resemble the plot of the random data. The

exceptions are the two-dimensional plots for week one, which seem to indicate a strong element of deterministic chaos.

Limit-cycle and Velocity Plot.

Priesmeyer and Baik used limit-cycle and velocity plots to uncover deterministic chaos in business cycles (Priesmeyer and Bailk, 1989:47). Likewise, Priesmeyer and Cole use a simpler process as a tool to manage disaster relief (Priesmeyer and Cole, 1996).

Before creating limit-cycle and velocity plots, two related variables are needed. This study uses the related variables of the value of federal contracts and the number of contracts becoming effective on each day. Since the limit-cycle and velocity plots are meant to be management tools, rather than to identify if deterministic chaos is present, the data was analyzed only using the one-week models. This also mimics the availability of data as it might be available to managers, on a weekly basis. Managers would then evaluate the cycle process at the end of the week to determine if they needed to make any changes to the current process. In reality, during a disaster this would probably be done on a daily basis; however, because of the limitations of the data, weekly information was used.

The result of the business model limit-cycle for each of the ten weeks is displayed below in figure 21. It can be seen in this figure that activity within each week was in all four quadrants of the Cartesian plane. The first week shows a pattern of strong first and third quadrant activity, the other weeks seem to oscillate along the x-axis. Since the oscillation appears on the horizontal axis, this may indicate it is a one-attractor system with random noise (Priesmeyer and Baik, 1989:18).

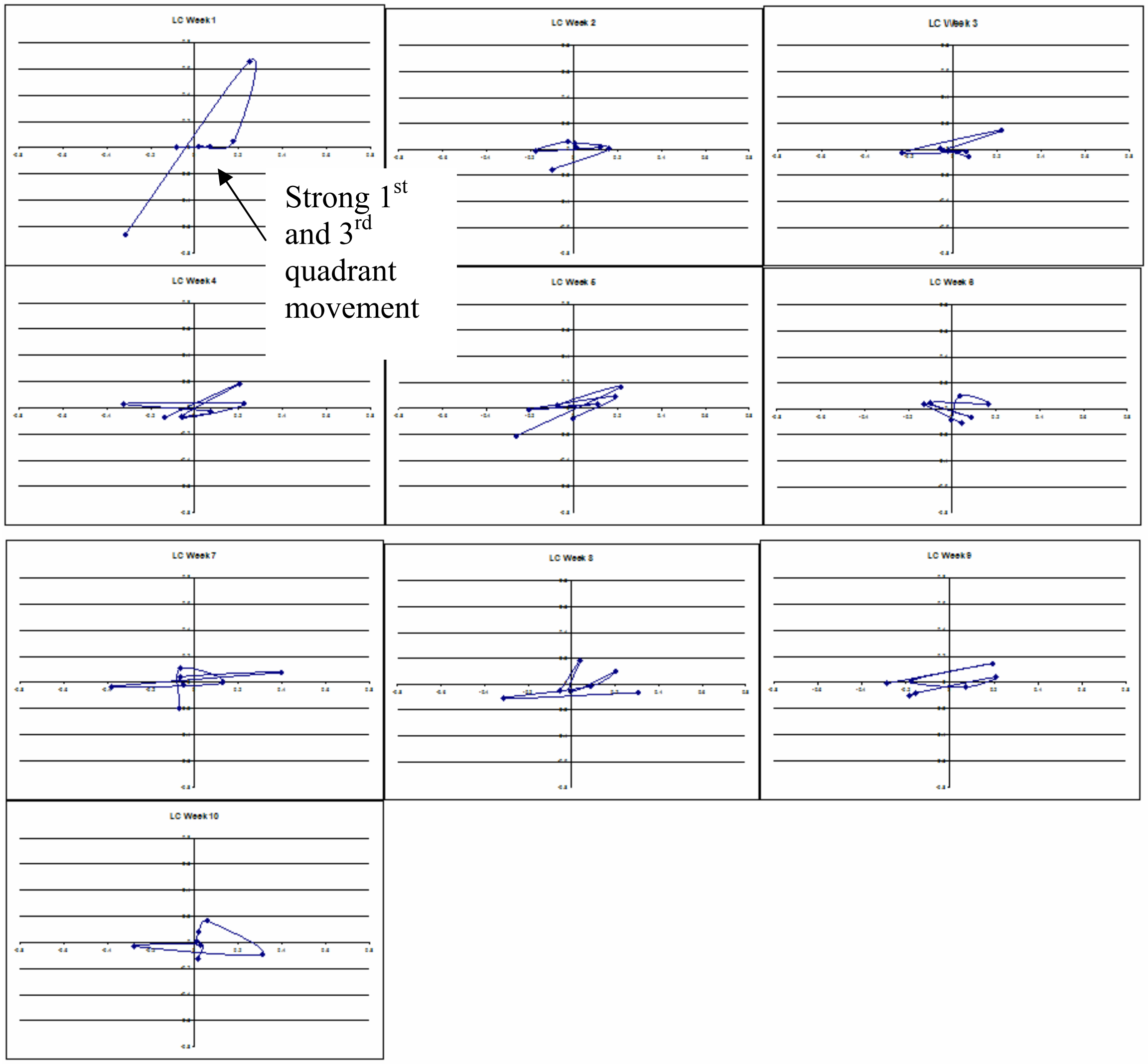


Figure 21. Business model limit-cycles for each of ten weeks

The cumulative limit-cycle, illustrated in figure 22, also shows the same pattern of activity in the first and third quadrants as well as a pattern of activity along the x-axis. In the examples presented by Priesmeyer and Baik, if a company was characterized by a one- to four-period attractor in the beginning, the rotation of data activity along the *x*-axis would be indicative of a movement toward chaos (Priesmeyer and Baik, 1989:21). That does not appear to be what is happening with the oscillation in this case. As mentioned in

the individual plots, after an initial shock to the first week, the plot appears to display a one-attractor system with random noise, with more variation in the dollar value of the contracts.

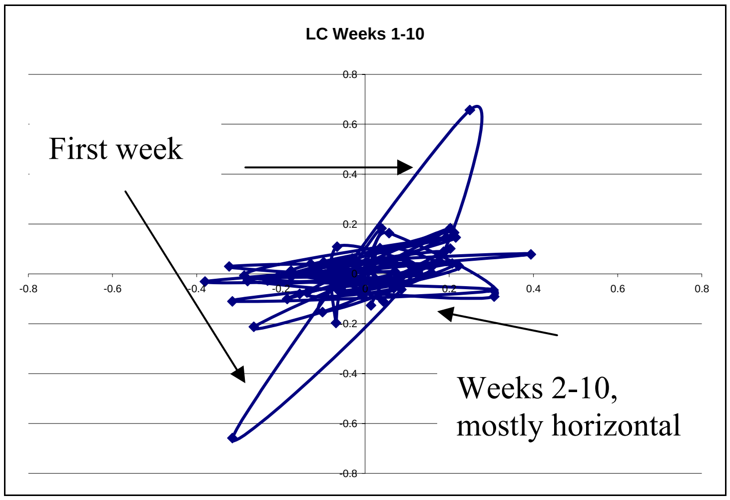


Figure 22. Business model, 10 one-week systems cumulative limit-cycle

The velocity plot of the data used in the business model in figure 23 shows no apparent pattern. It looks similar to the empirical data for one attractor companies in Priesmeyer and Baik's study. The ideal velocity plot for a one attractor company is a horizontal line, so the pattern is caused entirely by noise or random error (Priesmeyer and Baik, 1989:19).

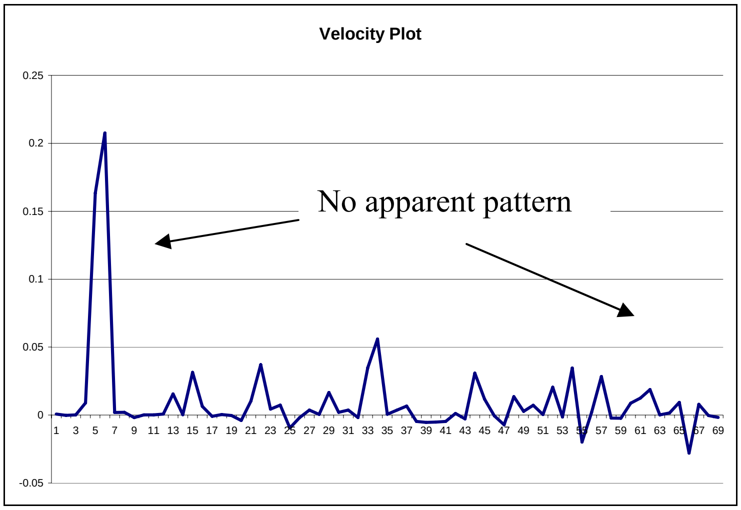


Figure 23. Business model velocity plot

This study uses contract value and the number of contracts measured as a percent of weekly totals as the variables in the disaster model limit-cycle. The information gathered from the disaster model limit-cycle has a different interpretation from the business model. Rather than looking for patterns to predict future business cycle activity, the plotted data are to make a diagnosis as far as whether more or less resources are needed, possibly indicating a change in the disaster response development. In the case of this study, data in the quadrants indicate the following:

Quadrant 1: Increase in both contract value and number

Quadrant 2: Increase in contract number but decreasing contract value

Quadrant 3: Decrease in both contract value and number

Quadrant 4: Increase in contract value but fewer contracts

The shape of the data in the weekly plots of the disaster model limit-cycle is not different than in the business model, it merely shifts its position on the Cartesian plane based on the mean change. In this case, the mean change is less than 0.003, so the shift is not

visually perceivable. However, since the location of the plot in relation to the *x*- and *y*-axis is important, the disaster model plot is available and exhibited in Appendix B. The plots in figure 21 and 22 above indicate that after the initial spike in the change in both the number of contracts and their value in week one, the number of contracts does not vary more than 20 percent. The change in value of the contracts varies by up to 40 percent, but most weeks the change is approximately 30 percent. It appears the plots might provide managers information concerning potential limits and cycle. This is especially true in the number-of-contracts data. The difficulty is in knowing whether the number of contracts suggests a limit to the number of people needed to award contracts, or does the number of people available to award contracts contribute to the limit exhibited in the plot? This difference would probably be resolved by a manager familiar with the system being observed.

Investigative Question answered by Limit-cycle and Velocity Plot.

Investigative question two explores whether the data reveal an underlying pattern that could be useful to management for decision making? Analyzing the data with the business limit-cycle reveals that the first week had strong activity in the first and third Cartesian plane quadrants. Depending on the other data this could be a spike associated with chaos, or an oscillation between two points. Based on the data in this study, the spike indicates movement into chaos. Weeks two through ten exhibited a limit on the resources not varying beyond 40 percent in contract-values and 20 percent in number-of-contracts data. If these limits are not the result of a workforce constraint, this information might be useful to management. It may indicate that from day to day the expected

change of contract values would not exceed 40 percent and therefore allow a prediction of worst case expected costs over a given timeframe.

Results and analysis conclusion

The Katrina contracting data was analyzed several ways. Initially, the raw data was plotted and spikes in data were linked to Katrina events, to see if they might offer an explanation. Then the empirical data was compared to the theoretical models.

The first model was the logistic equation. The data was analyzed using both ten-week systems and one-week systems. The ten-week systems indicated Katrina relief was stable, with one attractor, but the model could only explain approximately 30 percent of the variation at best. Closer fits were made using the one-week models ranging from a high correlation of 0.97 to a low of 0.37. The average correlation was 0.78 for the number-of-contracts data and 0.79 for the contracts-value. This suggests a strong relationship, but not necessarily the same line. The difference may be due to the addition of an element of randomness.

The next model was embedding the data. The data was embedded into three dimensions and visually inspected for evidence of deterministic chaos. This comparison found the ten-week systems undistinguishable from a similar system generated by random numbers. Likewise, combining the one-week systems into one database found them indistinguishable from a randomly generated one; this despite the fact the data was known to contain deterministic chaos. Consequently, if the known chaos model is not recognizable from random data; the empirical data likely will not be either. Therefore, the one-week empirical systems were not combined and embedded into three dimensions.

The final analysis of one-week systems uses two limit-cycle models, a business model and a disaster model. The result of the business model, suggested the evolving system had one attractor with random error or noise. The disaster model also identified potential system limits.

Taken together, except for the first week, the results of the tests for deterministic chaos are inconclusive. Analyzing the data as a ten-week system reveals the chaos model is not a good means of explaining the empirical dynamics. Utilizing one-week systems finds the chaos model more closely fitting the empirical data with the λ-parameter lying primarily in the chaotic region. Embedding the data in three dimensions found the ten-week system indistinguishable from chaos; however, embedding week one in two dimensions identified a good fit between the logistics model and empirical data.

V. Discussion and Recommendations

Relevance

The purpose of this research was to find out if an area of complexity science called chaos theory could be used to extract useful information from the Katrina contracting data that would help managers make better logistics decisions during disaster relief. This is relevant because if deterministic chaos is present in disaster relief operations, it would mean that events initially thought to evolve from random processes may actually be deterministic. Furthermore, initial conditions during disaster relief will have a significant affect on the disaster outcome and some of these outcomes will be unexpected. More importantly, it also means that some events during disaster relief that appear to develop from uncontrollable earlier events may actually be controllable.

This study also looked at two analytical techniques used by Priesmeyer and Cole to help disaster managers in decision making and to more effectively control disaster relief operations. For instance, it tested whether finding a logistic equation that closely fits the empirical data might provide feedback that would allow managers to determine the level of stability in the support provided for disaster relief. Also, the logistic equation might indicate if additional guidance/requirements on responders would be helpful or if it would nudge the support system into an area where control is lost. Another technique analyzed was the disaster limit-cycle model. The limit-cycle was used to see whether it could provide insight into what to expect in terms of the limit on resources and reveal cycles within the relief dynamics.

Reflections on the data

The result of looking at Katrina logistics support as ten-week systems did not reveal any evidence of deterministic chaos. Fitting a logistics regression line to the data, provided a significant fit, but could only explain 30 percent of the variation at best. Likewise, embedding the ten-week systems in three dimensions resulted in a plot that was indistinguishable from a plot created by embedding random data.

Analyzing the data in one-week systems resulted in more promising findings. Although, the fit of the empirical data to data generated by the logistic equation varied from week to week; the first week resulted in a close fit. Week one had a 0.97 correlation based on contract-values data, and a 0.95 correlation based on the number of contracts. Furthermore, the pattern created by embedding both systems into two dimensions resulted in distinct curves, somewhat like a horseshoe. This is characteristic of a purely deterministic chaos system with a stability level in the chaotic region. For instance, a two-dimensional plot of the same known chaos data exhibited in figure 9 creates a horseshoe shape. This is illustrated below in figure 24. This horseshoe pattern is evident in the empirical data from week one displayed earlier in figure 15.

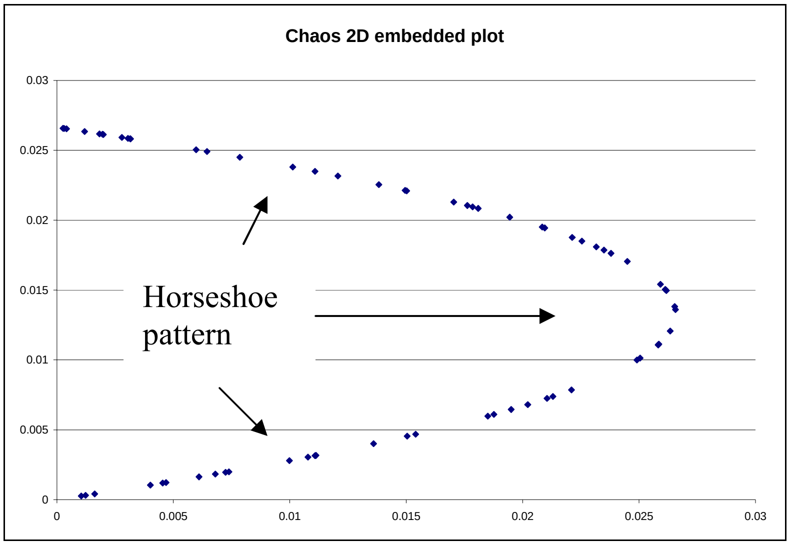


Figure 24. Two-dimensional plot of embedded time series, *X = 0.5, λ = 3.99*

Only data from the one-week systems were applied to the limit-cycle models. The models do not test whether deterministic chaos is present, but are models in which data containing deterministic chaos can be applied to reveal information concerning its dynamics. This study found that except for the first week, the business model limit-cycle plots exhibited what appears to be a single-point attractor with random noise. The velocity plot findings support this conclusion. This indicates that the business cycle is stable and that the variation is caused by random noise rather than by deterministic chaos. The first week displayed a spike well outside the "normal" cycle, which would indicate a system in the chaos region (with a λ-parameter value over 3.57). Furthermore, it indicates that the dynamic is an unstable business cycle and that the variation can be explained by chaos theory. Both the business model and disaster models exhibited a limit both in the amount of change in the number of contracts and in the value of the contracts. The disaster model does not appear to offer any useful information on the development of

the response based on the Cartesian quadrant in which activity takes place, but perhaps offers information on system limitations.

Research conclusion

This research found what appears to be an element of deterministic chaos during the first week of logistics support during Hurricane Katrina. This is based on the results of two tests. First, it was possible to find a logistic equation model that fit the empirical data at 0.95 or greater. Second, because when the empirical data from the first week is embedded in two-dimensions, it displays a pattern characteristic of a deterministic chaos system. Furthermore, although not a test of chaos, the limit-cycle model results of the first week support the level of chaos identified by the two tests. The tests for deterministic chaos in subsequent weeks, however, were inconclusive. Also, because the level of stability during the first week was in the chaotic region and deterministic chaos in subsequent weeks could not be substantiated, the analysis could not test the value of the logistics model as an indicator of bifurcations that might offer managers feedback on the effects of their decisions

The findings of this research conclude that initial conditions of disaster response will have a significant affect on the relief outcome and furthermore, some of the events during disaster relief that appear to evolve from uncontrollable events may be controllable. It is therefore likely that managers can control the evolution of disaster response by the decisions they make prior to and during the disaster. Unfortunately, this study was not able to substantiate the effectiveness of management tools such as matching the logistic equation to empirical data to identify bifurcation points in the system or using the disaster model limit-cycle to guide management decisions/policies.

Recommendation for further research

Further research into the application of chaos theory to disaster response should provide further understanding of this phenomenon and perhaps lead to more efficient disaster response. One area for further research is changing the measurements used in this study. For instance, the data in this study was limited to logistics activity measured by day and the most responsive systems consisting of seven days. Having data measuring logistics activity by hour could allow a more robust analysis of what is happening during the first week of logistics support. It may even be possible to look at how stable the system is on a daily basis. Likewise, logistics activity may be measured using something besides contracts, such as by disaster commodities like water or meals served. This study was concerned with federal logistics support; however, other logistics support systems could be evaluated. For instance, did state or private relief agencies behave similarly as federal activity?

Another area of research is in conducting a similar case study, but in parallel with other cases. This study looked at one disaster, Hurricane Katrina. Priesmeyer and Cole looked at several disasters with the data combined into one data set. Another possibility is to compare two or three disasters with each other and with the theoretical model. Does logistics support in similar disasters develop similarly? For instance, do all hurricanes have the same level of stability in the first week?

A final area of further research is looking at another branch of chaos theory concerned with the spatial evolution of a system. For instance, how did the logistic support evolve geographically? Did relief begin in several areas in isolation and then

combine as the relief capability grew? Did it evolve in the way that fractional chaos would expect?

Summary

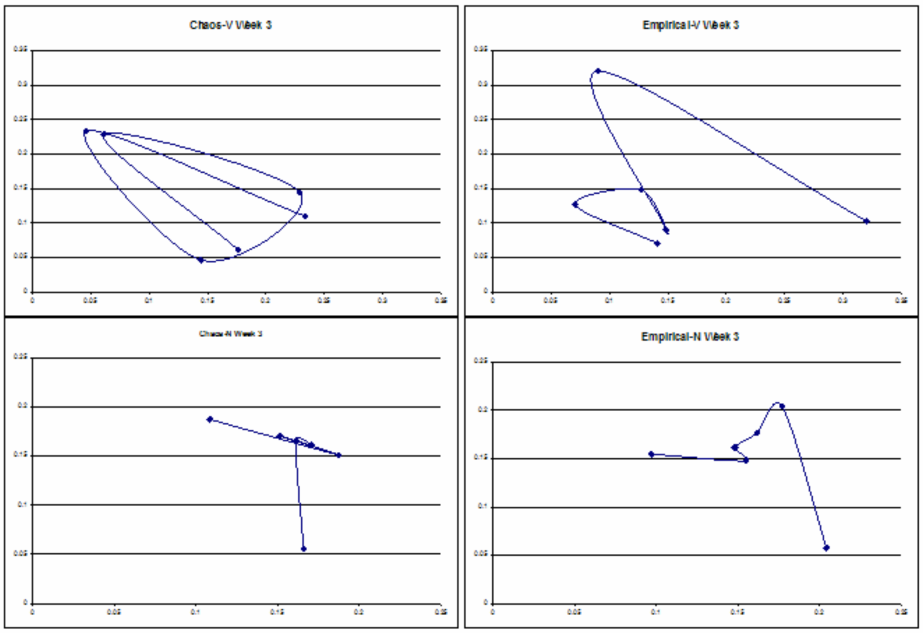
This study provided some answers to the research questions, but could not fully address the issue of using chaos theory to improve management practices during disaster relief. This is due to inconclusive results in this study on the usefulness of the management tools presented. Also, the scale used to measure the dynamics of the system created another limitation. It was not small enough to capture the detail necessary to catch changes in the level of stability. Nevertheless, the research does support the argument that there is an element of deterministic chaos in some logistics activities during disaster relief.

Finding deterministic chaos during the first week of Katrina suggests a justification for using chaos theory at least metaphorically to understand logistics support during catastrophic disaster relief. Consequently, the research findings support the conclusion that initial conditions of disaster response will have a significant affect on the relief outcome. Furthermore, some of the events during disaster relief that appear to evolve from uncontrollable events may be controllable. Therefore, managers are likely able to control the evolution of disaster response by the decisions they make prior to and during the disaster. This is especially true during the initial relief effort. In her research, Murphy uses the examples of the Exxon Valdez oil spill and the Johnson & Johnson Tylenol tampering event as contrasting cases of how disaster response can evolve. In the case of Exxon, slow reaction to remedy the problem enabled a negative public perception to evolve whereas in the case of Johnson & Johnson, quick action led to a positive public

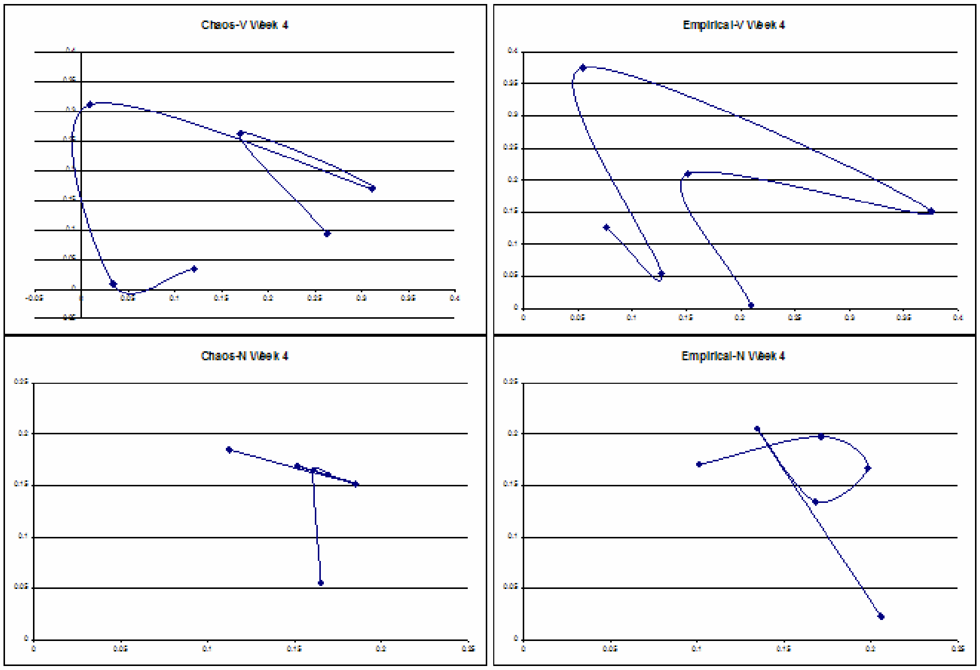
perception (Murphy, 1996). One can only speculate how differently the relief during Katrina could have evolved if managers had taken advantage of preparation prior to landfall and made quick, decisive actions early in the disaster response. Looking at the problems relating to communication, supply chain management and organizational behavior, it is clear that better preparation and clear, decisive action early in the disaster would have alleviated some of the problems. The chaos of Katrina need not have been so uncontrolled.

Appendix A

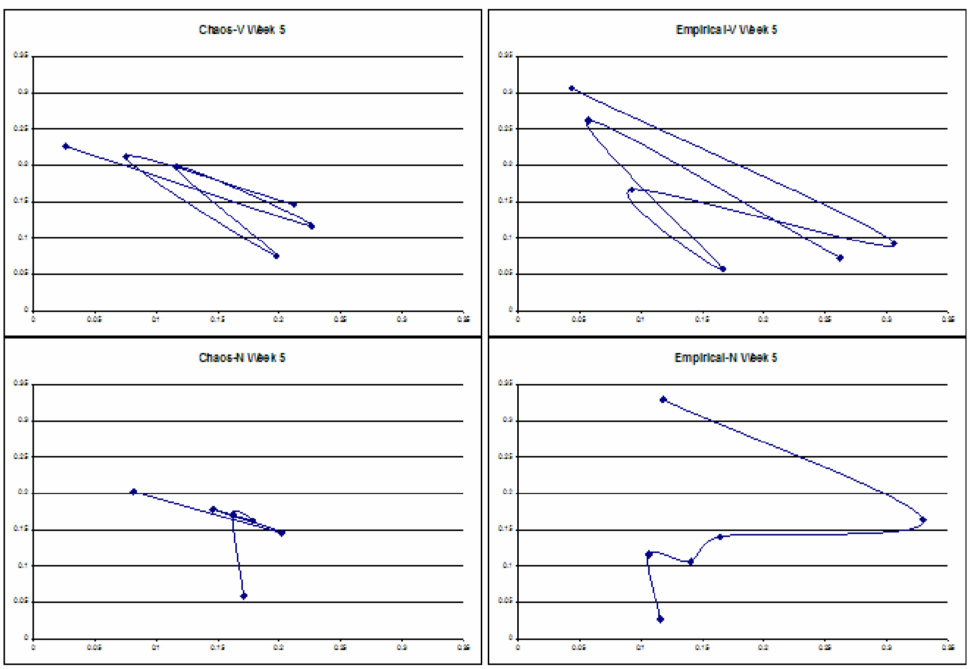
Plots for weeks three through ten are embedded in two-dimensions. In the figures, plots based on contract-values data are on top, plots based on number-of-contracts data are on the bottom. They also have the data generated by the logistic equation on the left and the empirical data on the right.



Week 3


Chaos-V Week 4
Empirical-V Week 4
Chaos-N Week 4
Empirical-N Week 4

Week 4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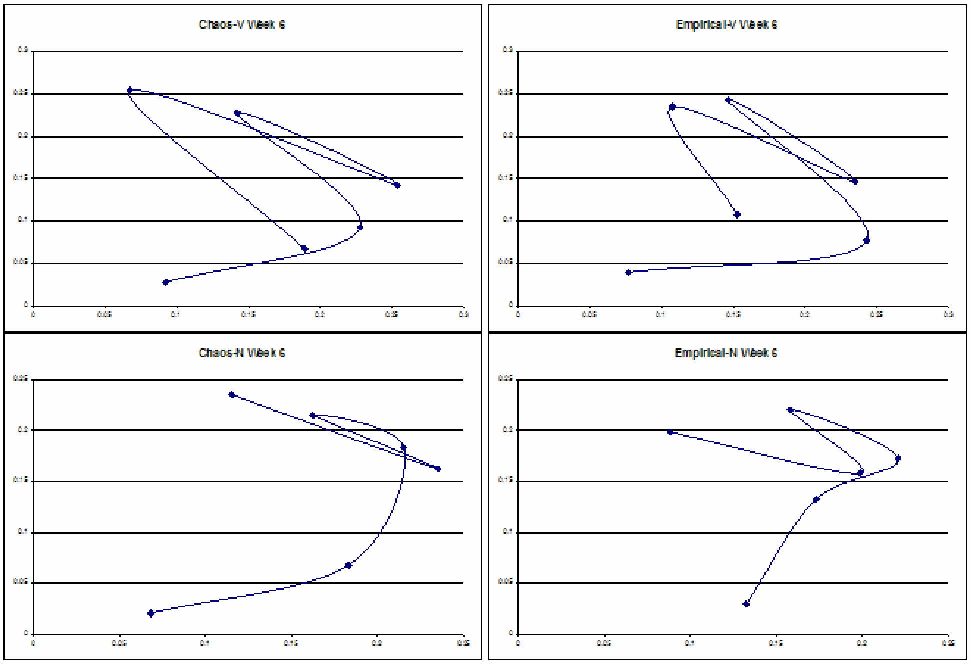
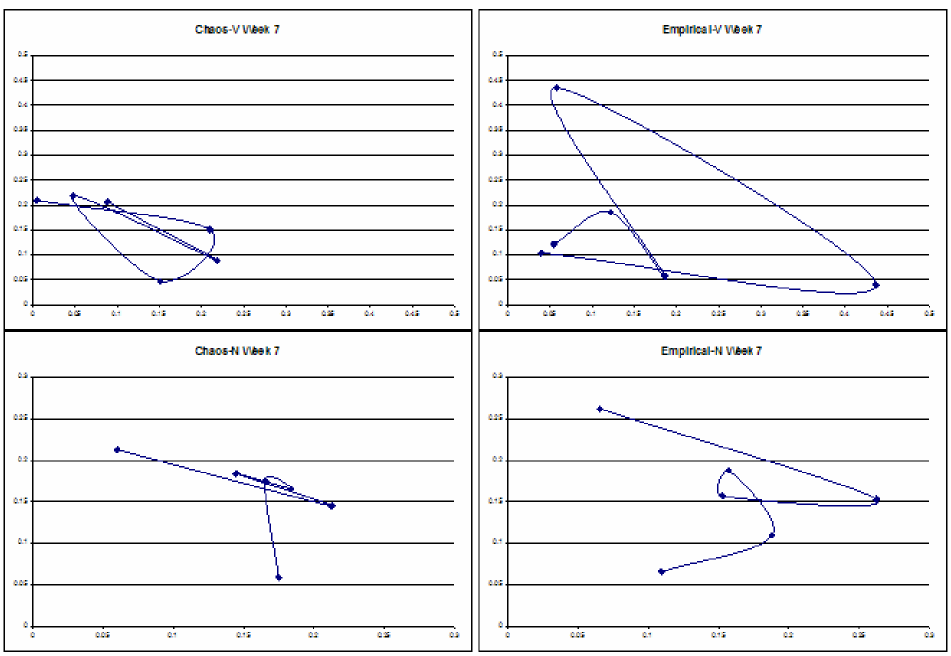
Empirical-V Week 5
Chaos-N Week 5
Empirical-N Week 5

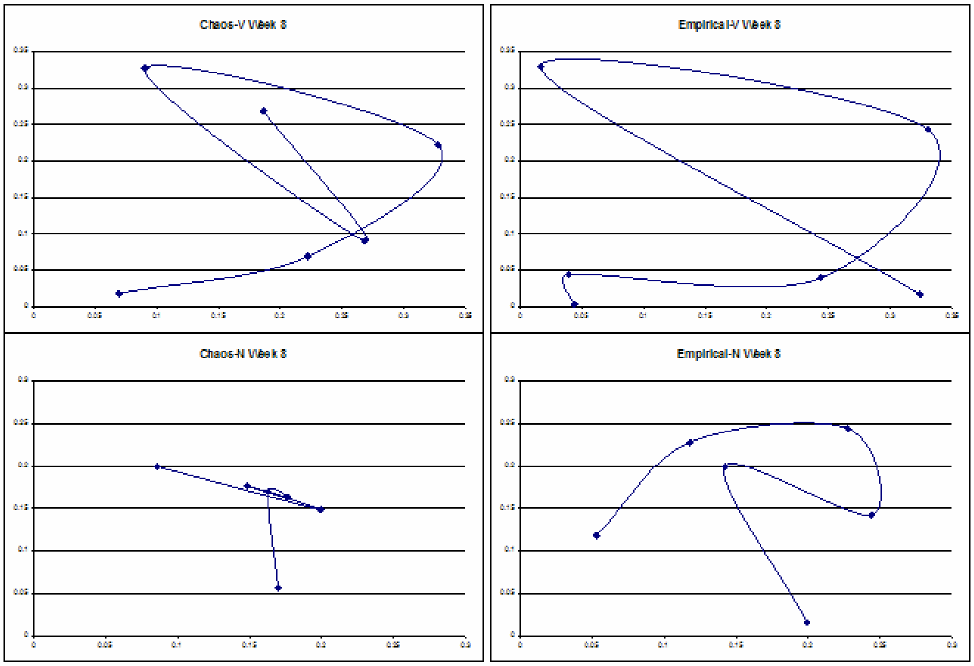
Week 5


Chaos-V Week 6
Empirical-V Week 6
Chaos-N Week 6
Empirical-N Week 6

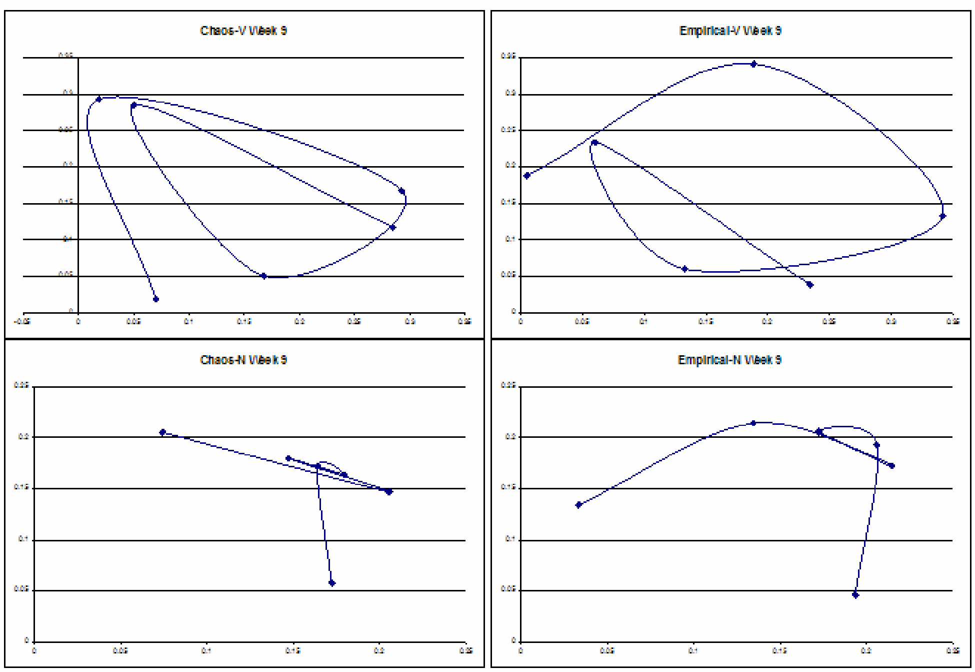
Week 6


Chaos-V Week 7
Empirical-V Week 7
Chaos-N Week 7
Empirical-N Week 7

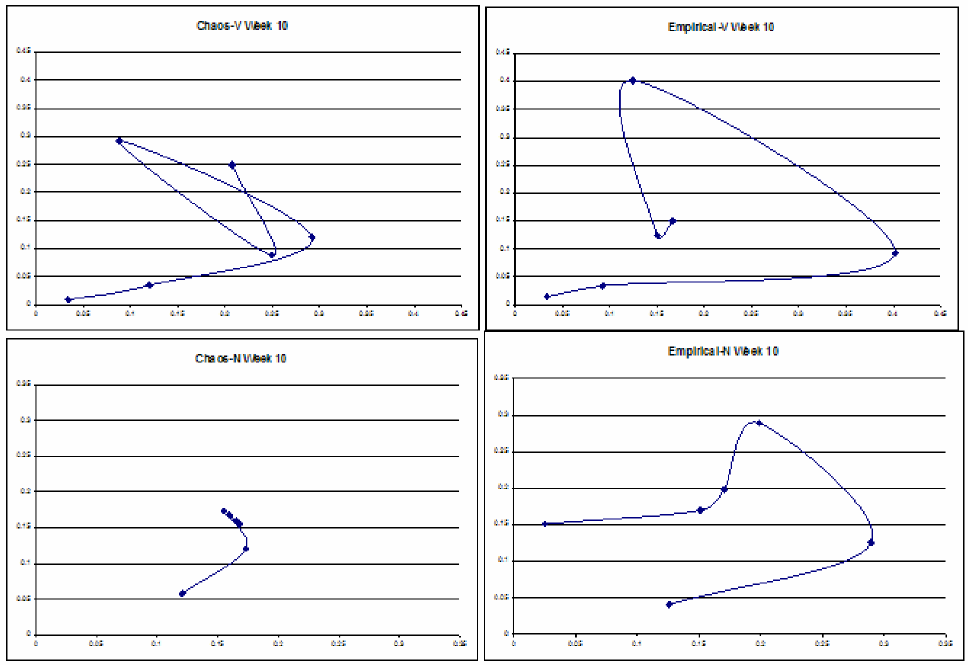
Week 7


Chaos-V Week 8
Empirical-V Week 8
Chaos-N Week 8
Empirical-N Week 8

Week 8


Chaos-V Week 9
Empirical-V Week 9
Chaos-N Week 9
Empirical-N Week 9

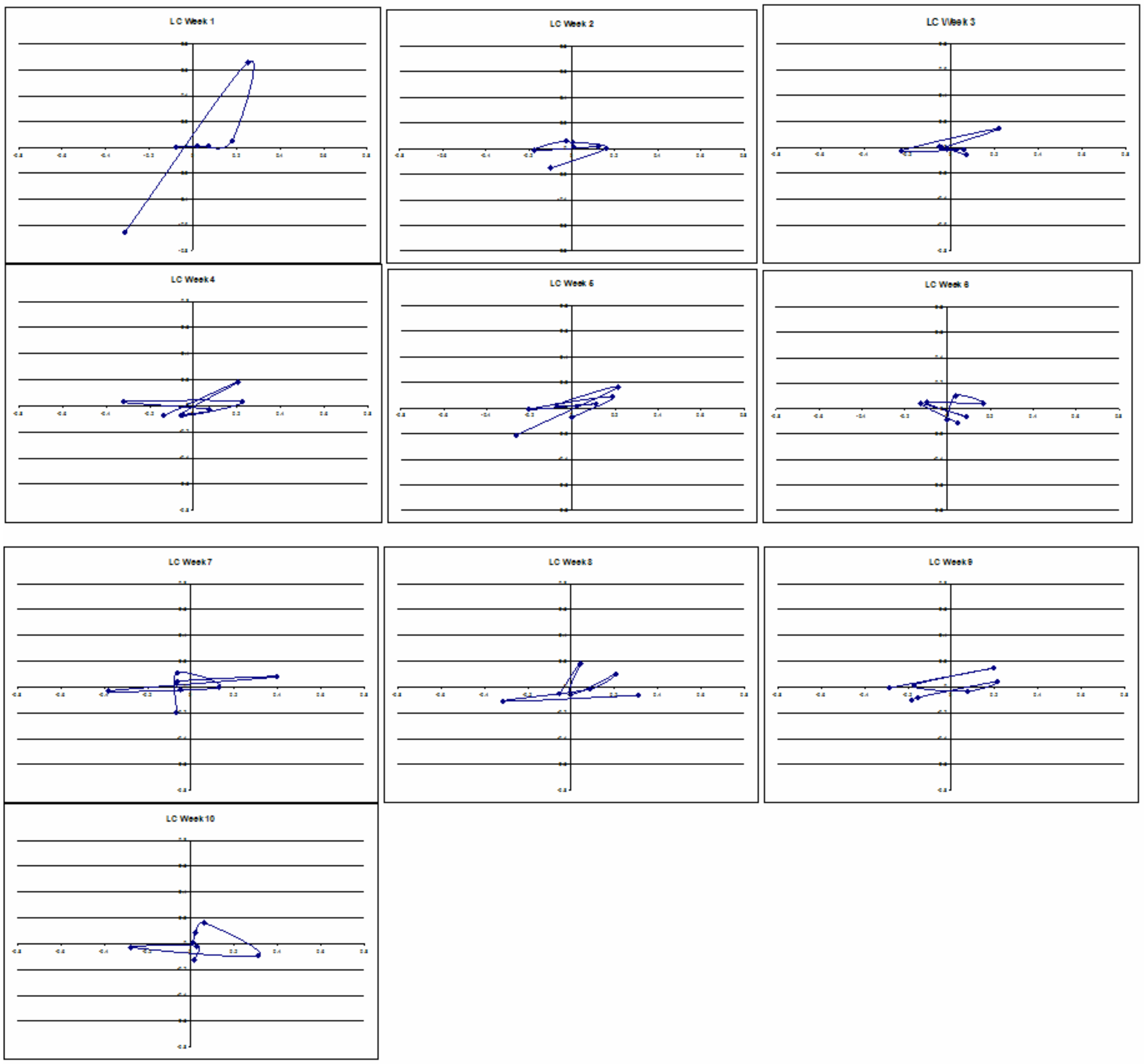
Week 9



Chaos-V Week 10
Empirical-V Week 10
Chaos-N Week 10
Empirical-N Week 10

Week 10

Appendix B



Disaster model limit-cycles for each of ten weeks

Bibliography

Ayers, James B. *Supply Chain Project Management: A Structured Collaborative and Measurable Approach*. Boca Raton FL: CRC Press LLC, 2004.

"Bifurcation Diagram." Excerpt from Wikipedia online encyclopedia. http://en.wikipedia.org/wiki/Bifurcation_diagram [8 December 2006]

"Big Disconnect, The," *CNN.com* (2 September 2005). http://www.cnn.com/2005/US/09/02/katrina.response/index.html [26 January 2007]

Carafano, James Jay, Senior Research Fellow, The Heritage Foundation. "Improving the National Response to Catastrophic Disaster," Statement before the Committee on Government Reform, House of Representatives. Washington DC: The Heritage Foundation. September 15, 2005.

"Chaos and Complexity Resources for Students and Teachers." Excerpt from Society for Chaos Theory in Psychology & Life Sciences webpage. 2006. http://www.societyforchaostheory.org/tutorials/ [26 January 2007]

Choi, Thomas Y., Kevin J. Dooley, and Manus Rungtusanatham. "Supply networks and complex adaptive systems: control versus emergence," *Journal of Operations Management*, 19: 351-366 (2001).

Clayton, Keith. "Basic Concepts in Nonlinear Dynamics and Chaos," *Proceedings from a workshop presented at the Society for Chaos Theory in Psychology and the Life Science.* Milwaukee, WI: Marquette University (31 July 1997). Published online. http://www.societyforchaostheory.org/chaosprimer.pdf [14 Nov 06]

Committee on Homeland Security and Governmental Affairs.

Hurricane Katrina: A Nation still Unprepared. Report on Homeland Security and Government Affairs, United States Senate. Washington DC: GPO, May 2006.

"Congress rushes $10.5 billion initial package of Katrina aid," *USToday.com* (2 September 2005). http://yahoo.usatoday.com/news/washington/2005-09-02-katrinacongressaid_x.htm?csp=1 [26 January 2007]

Cooper, David E. "Hurricanes Katrina and Rita Contracting for Response and Recovery Effort," Testimony Before the House Select Bipartisan Committee to Investigate the Preparation for and Response to Hurricane Katrina. Report GAO 06-235T. Washington: GPO, 2 November 2005.

"Death toll from Katrina likely higher than 1,300," Article from *MSNBC.msn.com*

webpage (10 February 2006). http://www.msnbc.msn.com/id/11281267/ [15 August 2006]

DHS (Department of Homeland Security). *Hurricane Katrina: What Government is Doing*. Excerpt from Department of Homeland Security webpage. http://www.dhs.gov/interweb/assetlibrary/katrina.htm [18 August 2006]

DHS. *Emergency Preparedness and Response Could Better Integrate Information Technology with Incident Response and Recovery*. OIG-05-36. Washington: GPO, September 2005.

"Disaster Management: Improving the Nation's Response to Catastrophic Disasters," Report to Congressional Requesters. Report GAO/RCED-93-186. Washington: GPO. July 1993.

Gibson, J.L., Ivancevich, J.M., Donnelly, J.H., Jr., Konopaske, R. *Organizations: Behavior, Structure, Processes,* (12th ed). New York: McGraw Hill/Irwin. 2006.

Glass, Niel. "Chaos, Non-linear Systems and Day-to-day Management," *European Management Journal*, 14.1: 98-106 (February 1996).

"Global Warming." Excerpt from National Oceanic and Atmospheric Association Webpage, 3 February 2006. http://www.ncdc.noaa.gov/oa/climate/globalwarming.html [18 August 2006]

Harrison, David M. *An Introduction to Chaos* (Version 1.26). Toronto, Canada: University of Toronto, published online, 2006. http://www.upscale.utoronto.ca/GeneralInterest/Harrison/Chaos/Chaos.html [4 January 2007].

"Henri Poincaré." Excerpt from online article. http://www-chaos.umd.edu/misc/poincare.html [27 January 2007]

James, Glenn E. "Chaos Theory: The Essentials for Military Application," *Newport Papers* (10th in the series). Newport, RI: Naval War College, October 1996.

Laugesen, Jocob and E. Mosekilde. "Border-collision bifurcations in a dynamic management game," *Computers & Operational Research*, 33: 464-478 (2006).

Leedy, Paul D. and Jeanne Ellis Ormrod. *Practical Research: Planning and Design* (8th Edition). Upper Saddle River NJ: Pearson Merrill Prentice Hall, 2005.

Leonard, Herman B. and Arnold M. Howitt. "Katrina as a Prelude: Preparing for and

Responding to Future Katrina-Class Disturbances in the United States," Testimony before the U.S. Senate Homeland Security and Governmental Affairs Committee, Washington: GPO, 8 March 2006.

"Katrina Contracts." Excerpt taken from NPDS-NG (National Procurement Data System – New Generation) provided by Project on Government Oversight. 2007. http://www.fpdsng.com/downloads/top_requests/katrina_contracts.xls [4 January 2007]

Kerr, Richard A. "Is Katrina a Harbinger of Still More Powerful Hurricanes?" *Science*. 309: 1807 (16 September 2005).

Koehler, Gus A. "What Disaster Response Management Can Learn From Chaos Theory," *Proceedings from Conference, What Disaster Response Management Can Learn From Chaos Theory Conference*. Sacramento, CA: California Research Bureau, published online, 1996 http://www.library.ca.gov/CRB/96/05/index.html [19 May 2006]

Makridakis, Spyros, Steven C. Wheelwright, and Rob J. Hyndman. *Forecasting Methods and Applications*, (3rd Edition). Hoboken, New Jersey: John Wiley & Sons. 1998

Murphy, Priscilla. "Chaos Theory as a Model for Managing Issues and Crises," *Public Relations Review*, 22.2: 95-113 (Summer 1996).

"NIMS online.com." Excerpt taken from online publication provided by EMAC International, LLC. http://www.nimsonline.com [16 August 2006]

Poole, Catherine and Bob Welch. Responding to Katrina, Acquisitions Directions Advisory (September 2005). Oakton, VA: Acquisitions Solutions Research Institute.

"Position Paper on Global Warming." Excerpt from The Weather Channel webpage, December 2005. http://www.weather.com/encyclopedia/global/index.html [18 December 2006]

Priesmeyer, H. Richard, and Edward G. Cole. "Nonlinear Analysis of Disaster Response Data," *Proceedings from Conference, What Disaster Response Management Can Learn From Chaos Theory Conference.* Ed. Gus A. Koehler. Sacramento, CA: California Research Bureau, published online, 1996. http://www.library.ca.gov/CRB/96/05/index.html [19 May 2006]

Priesmeyer, H. Richard, and Kibok Baik. "Discovering the Patterns of Chaos," *Planning Review*, 17.6:14-21,47 (November-December 1989).

Rosenhead, Jonathan. *Complexity Theory and Management Practice*. Published online,

1998. http://human-nature.com/science-as-culture/rosenhead.html [8 December 2006]

Singh, Harvir and Amarjit Singh. "Principles of Complexity and Chaos Theory in Project Execution: A New Approach to Management," *Cost Engineering*, 44.12: 23-33 (12 December 2002).

Shockley, K. "Cross recurrence quantification of interpersonal postural activity," *Tutorials in Contemporary Nonlinear Methods for the Behavioral Sciences*. Ed. Michael A. Riley and Gut C. Van Orden. Arizona State University and National Science Foundation. Published online, 2005. http://www.nsf.gov/sbe/bcs/pac/nmbs/nmbs.jsp [26 December 2006]

Townsend, Francis Fragos, Assistant to the President for Homeland Security and Counter Terrorism. "The Federal Response to Hurricane Katrina: Lessons Learned," Report to the President of the United States of America, Washington: GPO, 23 Feb 2006. http://www.whitehouse.gov/reports/katrina-lessons-learned/ [18 August 2006]

Vitasek, Kate. *Glossary of Terms*. List of definitions used by the Council of Supply Chain Management Professionals, Published online, 2006. http://www.cscmp.org/Downloads/Resources/glossary03.pdf [20 August 2006]

Webster, P.J and others. "Changes in Tropical Cyclone Number, Duration, and Intensity in a Warming Environment," *Science*. 309:1844-1846 (16 September 2005).

"What is Chaos Theory?" Except from unpublished article. http://iit.ches.ua.edu/systems/chaos.html [26 December 2006]

Wilding, Richard. "The ghost in the machine Chaos in supply chains is more likely to be generated by the systems we use than by external events writes Richard Wilding," *The Financial Times*, pg 5 (7 April 2006).

Wolk, Martin. "How Hurricane Katrina's costs are adding up," *MSNBC.msn.com* (13 Sep 2005). http://www.msnbc.msn.com/id/9329293/ [18 August 2006]

Yin, Robert K. *Case Study Research Design and Methods* (3rd Edition). Thousand Oaks, CA: Sage Publications, Inc., 2003

Young, T. R., L. Douglas Kiel. *Chaos and Management Science: Control, Prediction and Nonlinear Dynamics.* Published online, December 1994. http://critcrim.org/redfeather/chaos/029management.html [15 November 2006]

Youngbluth, Terry R. *A Post-Hurricane Andrew Review of Trends A Post-Hurricane*

Andrew Review of Trends in Department of Defense Disaster Relief Operations. Unpublished document, 15 April 1996. http://chppm-www.apgea.army.mil/news/A%20POST-HURRICANE%20ANDREW.doc [18 August 2006]

Zim, Alan D. "Derivation of a Logistics Equation for Organizations, and its Expansion into a Corporate Simulation," *Computational & Mathematical Organization Theory*, 11: 37-57 (2005).

Vita

Captain Gerald W. Morris Jr. graduated from Kamiakin High School in Kennewick, Washington. He enlisted in the Air Force in 1983 and spent fifteen years as a Surgical Technician at various assignments culminating at the 72d Medical Group, Tinker AFB, Oklahoma. He entered undergraduate studies at Southern Nazarene University, Oklahoma where he graduated with a Bachelor of Science degree in Organizational Leadership in May 1997. He was commissioned through Officer Training School, Maxwell AFB, Alabama in 1999.

His first commissioned assignment was as a supply officer to the 49th Materiel Maintenance Support Squadron, Holloman AFB, New Mexico. In November 2001, he was assigned to the 352d Operations Support Squadron, RAF Mildenhall, United Kingdom where he served as Chief of Contingency Plans and Lead Crisis Team Executive. While stationed at RAF Mildenhall, Captain Morris was reassigned to the 100th Logistic Readiness Squadron, as the Vehicle Management Flight Commander. In August 2005, he entered the Graduate School of Engineering and Management, Air Force Institute of Technology. Upon graduation, he will be assigned to the Air Force Logistics Management Agency.

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14. ABSTRACT
This study is a case study of federal logistics support during Hurricane Katrina disaster relief operations. Data from federal contracts covering the first ten weeks of Katrina are used to measure federal logistics activity. The study investigates whether chaos theory, part of complexity science, can extract information from Katrina contracting data to help managers make better logistics decisions during disaster relief. The study uses three analytical techniques: embedding, fitting the data to a logistic equation, and plotting the limit-cycle. Embedding and fitting a logistic equation to the data were used to test for deterministic chaos. The logistic equation and two versions of the limit-cycle model developed by Priesmeyer, Baik and Cole were also tested as potential management tools.
This study found deterministic chaos was present during the first week of disaster relief, but inconclusive results for subsequent weeks possibly due to internal changes to the relief dynamics. The research concludes that the initial conditions and early actions will have a significant affect on disaster relief outcome. Furthermore, many events that appear to be uncontrollable and random may actually be controllable. Therefore, managers play a critical role in preparing for and providing guidance in the early stages of disaster relief.

15. SUBJECT TERMS

Hurricane Katrina, Logistics, Contracting, Chaos Theory, Disaster relief, Deterministic chaos, Complexity Theory, Complexity Science, Management

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U	U	U	UU	104	(937) 255-3636, ext 4646; e-mail: Bradley.Anderson@afit.edu

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